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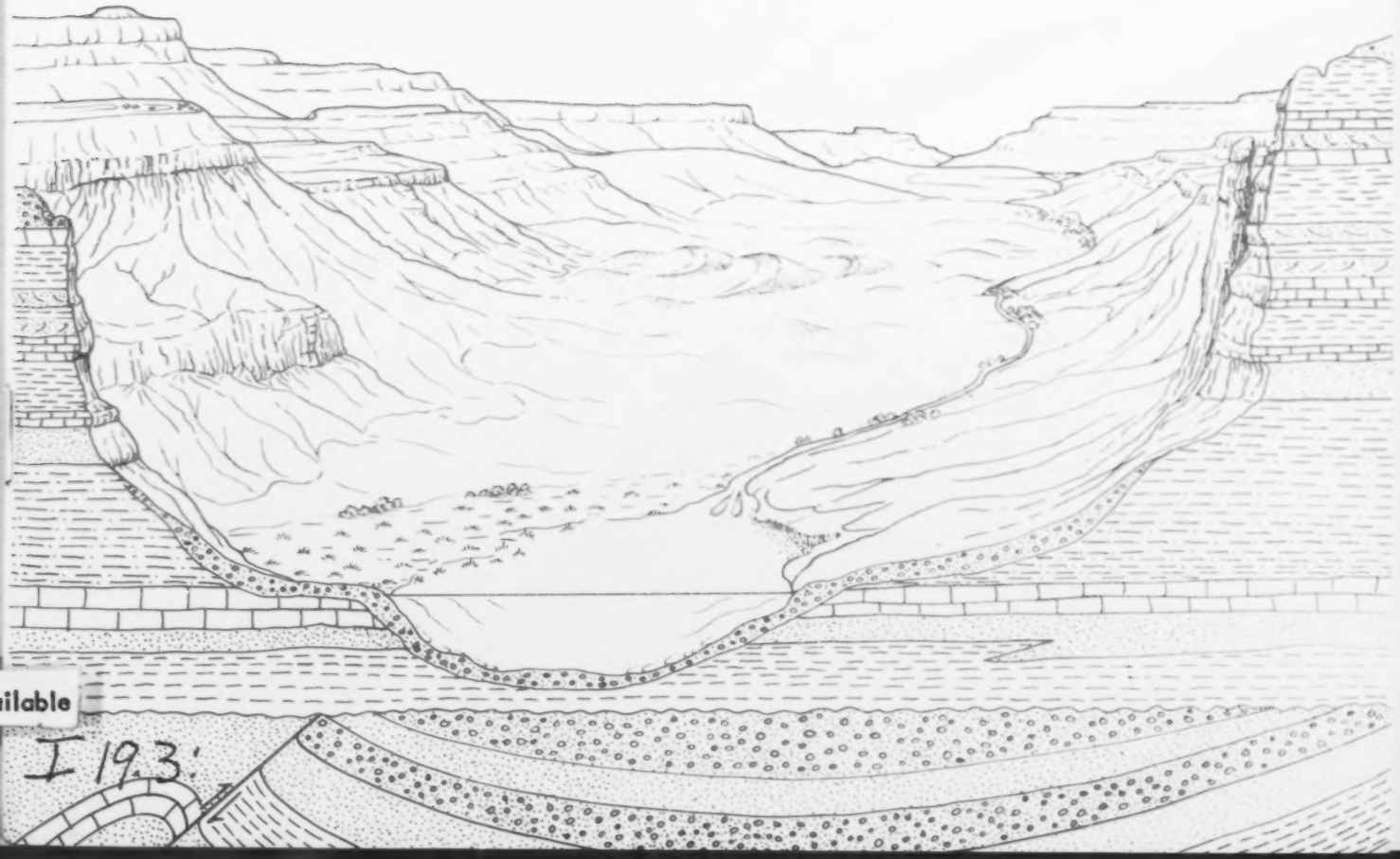

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Chapters B-D are issued as a single volume and are not available separately

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EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

DEPARTMENT OF THE INTERIOR
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Chapter B

Depositional Environments of the Upper Triassic Chinle Formation in the Eastern San Juan Basin and Vicinity, New Mexico

By RUSSELL F. DUBIEL

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

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CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C = (temp °F–32)/1.8

Depositional Environments of the Upper Triassic Chinle Formation in the Eastern San Juan Basin and Vicinity, New Mexico

By Russell F. Dubiel

Abstract

The Upper Triassic Chinle Formation is a sequence of continental strata exposed in the eastern San Juan basin along hogbacks on the western margin of the Nacimiento Mountains and north of the Nacimientos in the Chama basin. In this area, the Chinle Formation is composed of four formal and two informal members. In ascending order, these are the Agua Zarca Sandstone Member, the sandstone member, the Salitral Shale Tongue, the Poleo Sandstone Lentil, the Petrified Forest Member, and the siltstone member. The Agua Zarca, the sandstone member, and the Poleo are ledge-forming units composed primarily of sandstone and conglomerate. The Salitral Shale Member, the Petrified Forest Member, and the siltstone member are slope-forming units composed of siltstone, mudstone, and varying amounts of sandstone. The Chinle Formation unconformably overlies Permian rocks and is unconformably overlain by the Middle Jurassic Entrada Sandstone.

The Chinle Formation was deposited in a complex fluvial-deltaic-lacustrine system in the area of the present-day eastern San Juan basin and Chama basin. Lithofacies include conglomerate and planar- and trough-crossbedded sandstone; bentonitic mudstone and sandstone; black, organic carbon-rich mudstone; large-scale, trough cross-stratified siltstone, sandstone, and mudstone; and thick-bedded, bioturbated, fine-grained sandstone and siltstone. These lithofacies are interpreted as deposits of fluvial channels, adjacent floodplain crevasse splays and mudflats, lacustrine-deltaic channels and crevasse-splay systems, and lacustrine marshes and basins. Fluvial-channel and overbank sandstones and mudstones locally exhibit color-mottled, gleyed paleosols. Floodplain mudstones locally exhibit carbonate nodule-bearing vertisols.

Paleovalleys were initially eroded into underlying Permian rocks by degradational fluvial systems. Subsequent deposition by aggrading Chinle depositional systems then filled the paleovalleys with fluvial and marsh deposits. Fluvial, marsh, and deltaic complexes supplied sediment to lacustrine basins, prograded into the basins, and filled the basins with continental deposits.

Faunal assemblages, including evidence from lungfish burrows and invertebrate ichnofossils, and paleosols associated with specific lithofacies contribute to the understanding of depositional environments, paleoclimatology, and paleoecology of the Chinle. Lithofacies assemblages, fauna and flora, and paleosols indicate that the climate during deposition of the Chinle in the area of the eastern San Juan basin can be characterized as tropical monsoonal with abundant precipitation and seasonally drier periods.

Manuscript approved for publication, March 3, 1989.

INTRODUCTION

The Upper Triassic Chinle Formation is exposed along the uplifts that bound the San Juan basin of the Southwestern United States on the west, south, and east, and the laterally equivalent Dolores Formation is exposed on the northern boundary of the basin (figs. 1, 2). These exposures provide outcrop evidence for interpreting the depositional environments and history of the Chinle Formation in the San Juan basin and vicinity. Stratigraphy and depositional environments of the Chinle and related rocks on the Colorado Plateau, including the San Juan basin, were summarized by Stewart and others (1972a), who generalized interpretations of small-scale depositional environments. The lithostratigraphic methods employed by Stewart and others (1972a) and the long distances between outcrops resulted in unre-

solved details of the depositional history of the Chinle.

Despite the limitations imposed by restricted outcrops and poor exposures of fine-grained units, recent advances in sedimentology, such as the development of facies models for continental systems, and recent investigations of three-dimensional outcrops of the Chinle in southeastern Utah permit interpretation of detailed depositional environments of the Chinle Formation in the San Juan basin. Lithofacies, lithofacies assemblages, and interpreted depositional environments in the San Juan basin are similar to those described for southeastern Utah (Dubiel, 1982, 1983a, b, 1984, 1985, 1986, 1987a, b) and represent an eastward extension of the Chinle fluvial-lacustrine system.

This report describes exposures of the Chinle Formation on the eastern side of the San Juan basin in hogbacks on the west side of the Nacimiento Mountains

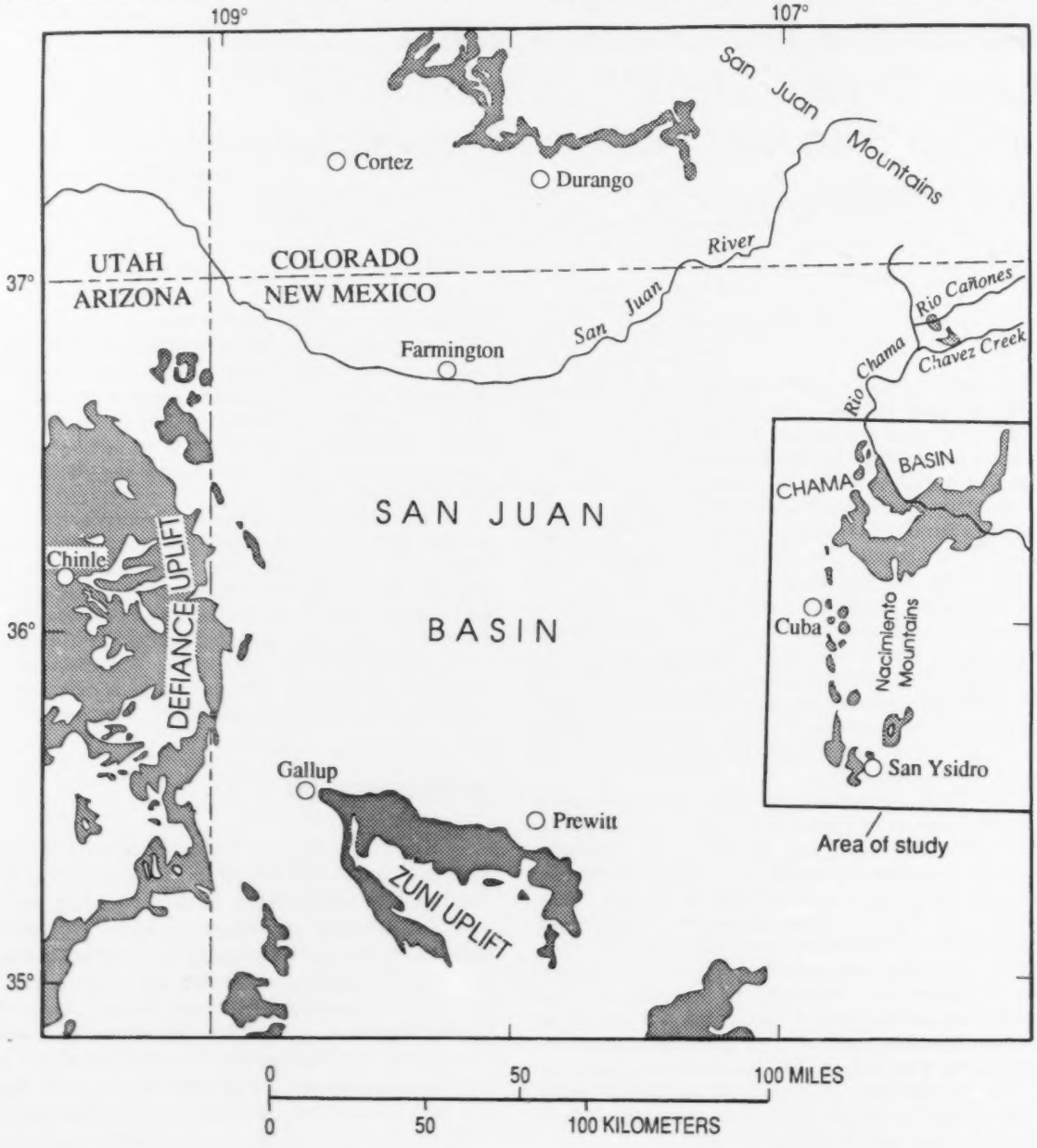

Figure 1. Location of study area and outcrop areas of Upper Triassic rocks (screen pattern), eastern San Juan basin. Modified from O'Sullivan (1977).

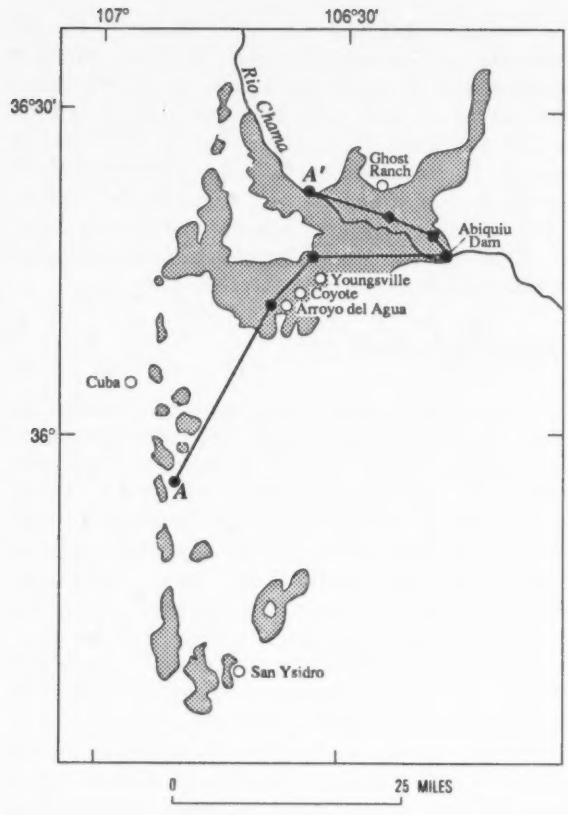

Figure 2. Outcrop areas of Triassic rocks in study area (screen pattern), locations of measured sections (solid circles), and line of section *A–A'* (fig. 3). Location of map area shown in figure 1; names of measured sections shown in figure 3.

and north of the Nacimientos in the Chama basin (fig. 2). By utilizing an analysis of depositional systems (see, for example, Miall, 1984) rather than a lithostratigraphic analysis, small-scale facies changes are recognized as a complicating factor in member designation and large-scale facies changes are employed as the key to Chinle depositional synthesis.

Problem and Setting

Triassic rocks in the Western United States were first described during the classic geological studies of the Colorado Plateau in the late 19th century (see Stewart and others, 1972a). The Chinle Formation was named by Gregory (1917) and subsequently has been studied extensively both by paleontologists for its vertebrate and plant fossils and by geologists for its uranium and vanadium deposits. More recently, advances in sedimentology have led to renewed investigation with emphasis on basin analysis.

A complex sequence of nomenclature development and stratigraphic correlation is an integral part of the Chinle Formation's history and is well summarized in Stewart and others (1972a, b) for the Colorado Plateau. Stewart and others (1959, 1972a) also made regional stratigraphic correlations of the Chinle and related formations on the Colorado Plateau. Regional stratigraphy, lithofacies, orientation of sedimentary structures, clay mineralogy, sedimentary petrology, characteristics of conglomerate layers, and paleontology all were combined to interpret the depositional history of the Chinle and related Triassic strata on the Colorado Plateau (Stewart and others, 1972a).

In order to interpret the depositional environments and history of the Chinle Formation in the eastern San Juan basin, the present study incorporates measured stratigraphic sections; recent advances in sedimentology, such as the development of detailed facies models (for example, Harms and others, 1975; Reineck and Singh, 1975; Reading, 1978; Walker, 1979, 1984; Leeder, 1982; Selley, 1982; Miall, 1984); and recent investigations of the Chinle Formation in southeastern Utah (Lupe, 1979; Gubitosa, 1981; Dubiel, 1982, 1983a, b, 1987a). Recognition of paleosols, observations of trace fossils, and incorporation of information on vertebrate and invertebrate fossils complement sedimentologic interpretations of the fluvial-lacustrine depositional systems. These combined data characterize the paleoclimate as tropical monsoonal during deposition of the Chinle Formation on the Colorado Plateau, including the area of the eastern San Juan basin.

Previous Investigations

Many of the early reports on the Chinle Formation describe either the paleontology or the uranium-vanadium deposits within its continental strata. It is beyond the scope of this report to summarize all of the minor publications that deal with individual fossil or mineral occurrences of the Chinle Formation in the eastern San Juan basin. In recent years, however, several publications have addressed the stratigraphy and depositional environments of the Chinle Formation relevant to the report area.

An inclusive review of previous investigations of the Chinle Formation on the Colorado Plateau is provided in Stewart and others (1972a), and a summary of Chinle nomenclature development is in Stewart and others (1972b). In addition, Stewart and others (1972a) presented correlations of the stratigraphy and interpretations of depositional environments, fossils, and paleoclimate of the Chinle Formation on the Colorado Plateau. Reviews of the Upper Triassic geology (O'Sullivan, 1974), vertebrate paleontology (Colbert, 1974), and megaplant fossils (Ash, 1974) are in a volume

on the area near Ghost Ranch, N. Mex. Trevena (1975) constructed depositional models for the Shinarump Member and the Sonsela Sandstone Bed of the Petrified Forest Member of the Chinle Formation in northeastern Arizona and northwestern New Mexico. O'Sullivan (1977) summarized the Triassic stratigraphy and made regional correlations in the area of the San Juan basin. Ash (1978) edited a volume of interdisciplinary studies of black mudstones interpreted to be lacustrine beds in the Monitor Butte Member of the Chinle Formation near Ft. Wingate, N. Mex. Kurtz (1978) and Kurtz and Anderson (1980) examined the sedimentology and the stratigraphy of the Chinle Formation in the eastern San Juan basin. Blodgett (1984) summarized depositional environments, trace fossils, and paleosols of the Dolores Formation in southwestern Colorado. The present investigation generally supports the interpretations of the previous Chinle studies but provides more detailed analysis of small-scale depositional environments and, in addition, new information on previously unrecognized Chinle Formation paleosols and trace fossils that are used to characterize Chinle paleogeography and paleoclimate.

Methods

This report focuses on Chinle outcrops in the eastern San Juan basin and draws comparisons with Chinle outcrops throughout the Colorado Plateau (Dubiel, 1987a). In the eastern San Juan basin, measured stratigraphic sections of the complete Chinle Formation in areas of good to excellent exposure were augmented with measured sections and observations of incomplete Chinle sections in areas of poor exposure. Additional stratigraphic sections of the Chinle Formation measured in western Colorado, in eastern and northern Arizona, and in southern Utah (Dubiel, 1982, 1983a, b, 1987a) were used to compare and contrast Chinle lithofacies and depositional systems over the entire Colorado Plateau.

Stratigraphic sections (fig. 3) were measured with an Abney level and Jacob's staff and are depicted as schematic columnar sections that include information on lithology, bedding, sedimentary structures, biogenic structures, paleosols, and paleocurrent indicators. A summary of these sedimentologic parameters, including descriptions and interpretations, can be found in Reading (1978), Walker (1979, 1984), Leeder (1982), Selley (1982), and Miall (1984) and references therein. Chinle depositional environments were interpreted from bedding and sedimentary structures, distribution and geometry of lithofacies, fossils and trace fossils, paleosols, vertical and lateral facies assemblages, and comparison of lithofacies assemblages in the study area with those in the Chinle at other localities.

Acknowledgments.—Dr. J. Michael Parrish, University of Colorado Museum, Boulder, provided identifications of vertebrate fossils, and Steve Good, University of Colorado at Boulder, provided information on Chinle mollusces. Dr. Judith T. Parrish, University of Arizona, Tucson, contributed to my understanding of tropical monsoons and climate. Assistants in the field include Willy Meyer, Mark Anderson, and Carmen Guité.

The staff at Ghost Ranch graciously provided permission to access outcrops on their property.

STRATIGRAPHY

In the eastern San Juan basin and vicinity, the Chinle Formation locally overlies several Paleozoic and older units. Although the Chinle Formation generally overlies Permian rocks (Stewart and others, 1972a; Kurtz, 1978), north of the study area it overlies Precambrian rocks near Rio Cañones and Pennsylvanian-Permian rocks near Chavez Creek (Stewart and others, 1972a). Locally, the contact with Permian rocks is disconformable, but the contact with Pennsylvanian-Permian rocks at Chavez Creek and with Precambrian rocks at Rio Cañones indicates that regionally the sub-Chinle surface is an angular unconformity. In most of the Nacimiento Mountains, Permian rocks consist of the undifferentiated Cutler Formation (Anderson, 1970; Stewart and others, 1972a). In the very southern part of the Nacimiento Mountains, Permian rocks are differentiated as the Wolfcampian Abo Formation and the Leonardian Yeso Formation (Baars, 1962; Stewart and others, 1972a).

The Chinle Formation in the eastern San Juan basin consists of four formal members and two informal members (Stewart and others, 1972a). In ascending order, these are the Agua Zarca Sandstone Member, the sandstone member, the Salitral Shale Tongue, the Poleo Sandstone Lentil, the Petrified Forest Member, and the siltstone member (fig. 3), although all members are not at every locality.

The basal sandstone unit of the Chinle in the San Juan basin has been given various names. The Agua Zarca Sandstone Member was named by Wood and others (1946) for exposures along Agua Zarca Creek near Coyote, N. Mex. (fig. 2). Wood and others (1946) extended the name Agua Zarca into the southern Nacimiento Mountains, but Stewart and others (1972a) felt this correlation was uncertain and informally named this unit at the base of the Chinle the sandstone member. The sandstone member was recognized by Stewart and others (1972a) to overlie the Agua Zarca in the northern Nacimiento Mountains. Kurtz (1978) recognized a basal Chinle sandstone near San Ysidro and informally named it after exposures on Red Mesa, located 5 mi (8 km) northeast of San Ysidro.

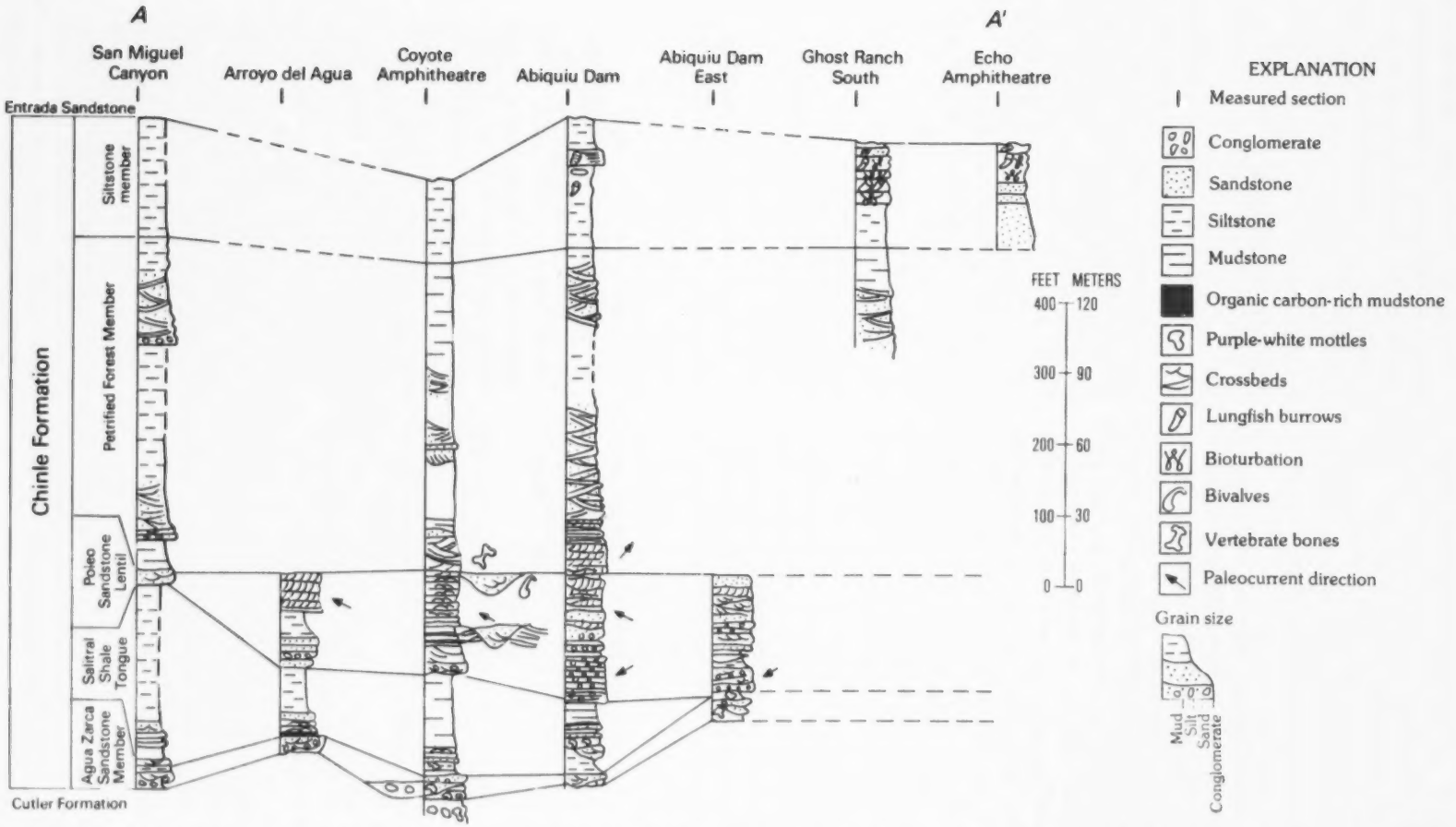

Figure 3. Schematic columnar measured sections of Upper Triassic Chinle Formation along line of section *A–A'* in the eastern San Juan basin. Locations of measured sections and line of section shown in figure 2.

The Agua Zarca Sandstone Member is a ledge-forming unit that everywhere has a sharp and erosional contact with the underlying Cutler Formation. The contact is irregular and generally characterized by large-scale lenticular scours that are filled with Agua Zarca. The Agua Zarca varies in thickness from 0 to about 100 ft (0–30 m).

The sandstone member was not differentiated during this study. Sandstones in this stratigraphic interval were placed either in the Agua Zarca Sandstone Member or in the Salitral Shale Tongue.

The Salitral Shale Tongue is a lithologically heterogeneous, fine-grained unit that generally weathers to a slope. The Salitral was named by Wood and others (1946) for exposures along Salitral Creek just west of Coyote, N. Mex. The Salitral contains purple-mottled siltstones and mudstones, yellow to brown sandstones, and green sandstones, siltstones, and mudstones. Chenoweth (1974) reported limestone beds in the Salitral in the canyon of the Rio Chama north of Coyote. The Salitral ranges in thickness from about 0 to 250 ft (0–75 m).

The Poleo Sandstone Lentil is a yellowish-gray to brown, fine- to medium-grained quartz sandstone that contains abundant red, yellow, and orange chert granules and pebbles. It is a cliff-forming unit that is recognizable from the northern part of the study area southward to where it pinches out north of San Ysidro, N. Mex. This study recognizes two distinct units in the Poleo near Abiquiu Dam; a lower conglomeratic unit and an upper, medium- to fine-grained, crossbedded unit, both of which were recognized by Kurtz (1978). The Poleo attains a maximum thickness of about 250 ft (75 m) at Abiquiu Dam.

The lavender to red and brown sandstones and variegated mudstones of the Petrified Forest Member conformably overlie either the Salitral Shale Tongue or the Poleo Sandstone Lentil. Where the Poleo is absent, sandstones and mudstones of the Petrified Forest and the Salitral are in contact and are difficult or impossible to distinguish from each other. The Petrified Forest Member is about 550 ft (165 m) thick in the large natural amphitheatre about 2 mi north of Coyote.

The Petrified Forest Member grades upward into the siltstone member. The siltstone member is composed of light-brown to reddish-brown siltstones and very fine grained sandstones and is distinguished from the underlying Petrified Forest by a color change from pastel red, lavender, and purple to brown and reddish brown. The siltstone member is about 200 ft (60 m) thick near Ghost Ranch. Because of generally poor exposures, this slope-forming member is difficult to recognize in other outcrops in the area.

The Middle Jurassic Entrada Sandstone unconformably overlies the Chinle Formation in the eastern San Juan basin. The Entrada is composed of light-orange to yellowish-white, thick-bedded, well-sorted quartz sandstone and exhibits large-scale trough cross-stratification.

SEDIMENTOLOGY

The facies in the various members of the Chinle Formation comprise a complex array of lithologies, sedimentary structures, and fossils. These facies have been interpreted as the result of deposition in a complex fluvial-lacustrine system (Stewart and others, 1972a; Blakey and Gubitosa, 1983; Dubiel, 1983b, 1984, 1985, 1987a, b). Measured stratigraphic sections (fig. 3) were utilized to identify process-controlled genetic units and to determine paleocurrent directions. Lithofacies were identified from individual outcrop exposures of lithostratigraphic units and from lateral facies associations deduced from measured sections and from poorly exposed unmeasured, but observed sections.

Sub-Chinle Unconformity

The Chinle Formation fills large scours eroded into the Cutler Formation and other Permian rocks by an episode of degradation that preceded Chinle deposition. The large scale of the scours that contain Agua Zarca Sandstone Member and their morphologic similarity to swales interpreted as Chinle paleovalleys in other areas (Witkind and Thaden, 1963; Stewart and others, 1972a; Blakey and Gubitosa, 1983; Dubiel, 1983b, 1987a) indicate that the scours should be interpreted as paleovalleys. Locally beneath the Agua Zarca scour fills, the red Permian rocks are altered by a distinctive purple and white mottled coloration. With increasing depth below the Agua Zarca, the mottled coloration decreases in intensity and bedding is less obliterated. These purple-mottled Permian units are identical to rocks referred to as mottled Moenkopi and as mottled strata of the Chinle by Stewart and others (1972a) and to rocks defined as the Temple Mountain Member of the Chinle in the San Rafael Swell of Utah by Robeck (1956).

The purple and white mottling of the Cutler Formation appears to be restricted to the flanks of Chinle paleovalleys that are filled with Chinle deposits. The mottled Cutler beds are interpreted herein as gleyed paleosols (see for example, Birkeland, 1984, p. 146) developed on Cutler rocks due to pedogenic alteration from shallow, fluctuating water tables associated with initial Chinle deposition in the paleovalleys. This agrees with the interpretation of alteration during formation of

a soil (Stewart and others, 1972a) and interpretations of gleyed basal Chinle paleosols in southeastern Utah (Dubiel, 1987a). However, the formation of the purple-mottled Cutler beds and similar mottled beds in overlying members of the Chinle indicates that soil formation was related to fluctuating water tables (Birkeland, 1984, p. 146) associated with the Chinle depositional system. A more detailed interpretation of the pedogenic processes is presented later in the report.

Chinle Formation

Interpretations of depositional environments are based on identification of lithofacies and lithofacies assemblages and on comparison of these facies associations to those present in more well exposed Chinle outcrops farther to the west on the Colorado Plateau (Dubiel, 1987a, b). Specific lithofacies, lithofacies assemblages, and their interpreted depositional environments reflect the complexity of Chinle continental depositional systems.

Paleosols and fossils or trace fossils were recognized in several depositional units and were incorporated into the depositional synthesis of the Chinle. Vertebrate remains, invertebrate fossils, and trace fossils found in various depositional and pedogenic units were integrated into the interpretations of depositional history and paleoclimate. Sedimentologic data relevant to interpreting Chinle paleogeography and paleoclimate are included in the following discussion.

Agua Zarca Sandstone Member

The Agua Zarca consists of white to yellow and gray, medium- to coarse-grained to conglomeratic quartz sandstone that is structureless to tabular-planar cross-bedded and grades upward into medium-grained, quartzose sandstone characterized by large- to medium-scale trough crossbeds and horizontal laminations (fig. 4). The Agua Zarca exhibits complex cut-and-fill structures and large-scale, lenticular internal scour surfaces (fig. 5). Gray, carbonaceous, horizontally laminated mudstone lenses occur locally in the Agua Zarca sandstones, and, in places, Agua Zarca sandstone bodies grade laterally into siltstone and mudstone lenses (fig. 5). The Agua Zarca is restricted to the lower part of paleovalleys eroded into the Cutler Formation. Lenticular sandstone bodies in the Agua Zarca (fig. 5) commonly are stacked but are laterally offset.

Lithology, sedimentary structures, and large-scale sandstone geometry indicate that the Agua Zarca Sandstone Member consists of fluvial strata deposited in the lowest parts of the paleovalleys cut into the Cutler Formation. The transition from massive, conglomeratic, and tabular-planar cross-stratified sandstone at the base of the Agua Zarca upward into medium-grained, trough cross-stratified sandstone, coupled with the lenticular geometry and lateral gradation to thin-bedded sandstone and siltstone, is thought to represent a change from bedload deposition in braided streams containing

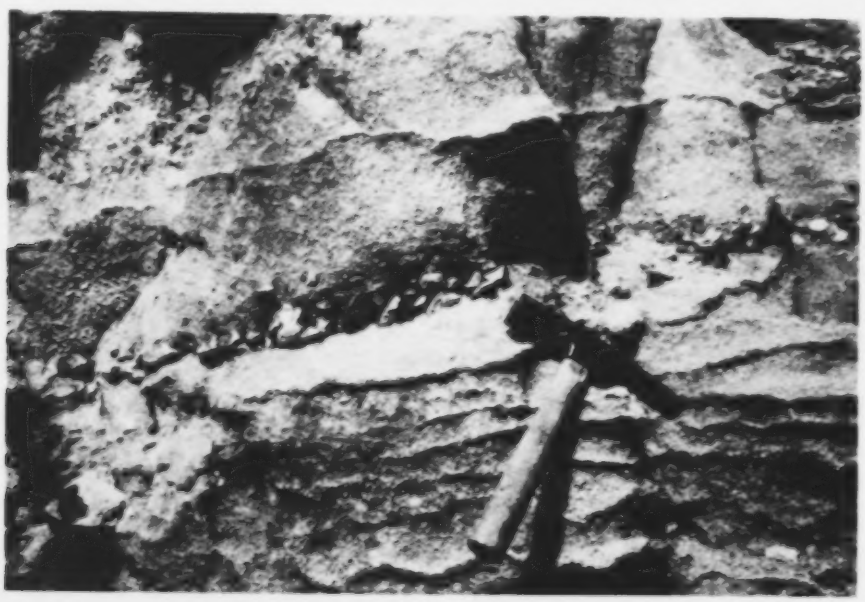

Figure 4. Agua Zarca Sandstone Member south of Cuba. Note sandstone contains thin conglomerate lens. Hammer shown for scale.

Figure 5. Lenticular channel-fill sandstone bodies of the Agua Zarca Sandstone Member (Tca) scoured into Permian Cutler Formation (Pc). View looking north; north of Youngsville, N. Mex.

transverse bars in the lower part of the unit to suspended- and mixed-load deposition in more sinuous fluvial systems containing sand waves in the upper parts of the unit.

Locally in outcrops north of Coyote and near Abiquiu Dam, Agua Zarca sandstones exhibit large purple, yellow, and white mottles that have an irregular shape and are as much as 6 in. (15 cm) across (fig. 6). In thin sections of mottled Chinle rocks in southeastern Utah (Dubiel, 1987a), the purple, yellow, and white mottles are shown to be a function of the mineralogy and concentration of iron-bearing minerals. Dense concentrations of hematite cement occur in the dark-purple areas, less hematite is in the lavender areas, limonite(?) (a hydrated iron compound) colors the yellow areas, and hematite is absent in white areas. The dark-bluish-black cast observed in many of the dark-purple mottles may be due to manganese compounds associated with the hematite (Birkeland, 1984, p. 147). The mottling of these rocks is thought to reflect shallow, fluctuating water tables within the sediments, probably in response to seasonal flooding (Dubiel, 1987a). The iron is interpreted to have been redistributed by pedogenesis within the ancient sediments when the fluctuating water tables alternated between oxidizing and reducing conditions.

The purple-mottled beds are interpreted as gleyed paleosols that formed on Chinle fluvial sandstone units subjected to fluctuating water tables at the time of deposition (Birkeland, 1984, p. 146). The purple and white mottling passes at the same level laterally from the Chinle into the uppermost parts of the Cutler. The mottling represents gleyed paleosols formed on the Cutler as the same fluctuating water tables affected iron content in both the Agua Zarca that filled paleovalleys and in the Cutler that formed the low-relief paleovalley walls.

Locally in the area north of Coyote, the mottled facies of the Agua Zarca can be traced laterally into purple-mottled and gray siltstones and black, organic-rich mudstones. The black mudstones are as thick as 5 ft (1.5 m). These genetically related, purple-mottled and organic-rich units are interpreted to represent coarse-grained clastic deposits of fluvial channel systems and fine-grained clastic and organic carbon deposits of adjacent overbank and lacustrine-marsh and bog wetland environments similar to those interpreted for the Chinle in southeastern Utah (Dubiel, 1984, 1987a). High organic productivity and preservation below the fresh-water tables of marshes and bogs resulted in the accumulation of organic-rich mudstones. These deposits are interpreted to represent organically productive

Figure 6. Agua Zarca Sandstone Member north of Arroyo del Agua. Pedogenic mottling between arrows developed as a result of fluctuating water tables in depositional environment. View looking north.

water-logged paleosols and can be classified as histosols (Buringh, 1968; Young, 1976). The occurrence of organic-rich mudstones necessitates a continually high freshwater table in order to preserve the organic material (Collinson, 1978).

Paleocurrent measurements of trough crossbeds within Agua Zarca sandstones (Kurtz, 1978) indicate a paleoslope to the southwest during deposition of the Agua Zarca Sandstone Member.

Sandstone Member

The sandstone member is recognized as the basal sandstone unit of the Chinle in the area near San Ysidro (Stewart and others, 1972a) and is well exposed at Red Mesa (Kurtz, 1978). The sandstone member is composed of orange to yellowish-gray, fine- to medium-grained quartz sandstone and minor conglomerate lenses containing pebbles generally less than 1 in. (2.5 cm) in diameter (Stewart and others, 1972a). Paleocurrent studies indicate north- to northeast-dipping cross-strata in the sandstone member (Stewart and others, 1972a).

The sandstone member typically exhibits medium-scale trough cross-stratification and large-scale cut-and-fill features, both of which are interpreted to represent deposition in fluvial systems. Depositional analysis of the sandstone member indicates only that the unit was deposited by north- to northeast-flowing, probably sinuous, streams.

Stewart and others (1972a) and Kurtz (1978) correlated the sandstone member with parts of the Agua Zarca Sandstone Member and the Salitral Shale Tongue. However, the generally poor exposures, the extensive vegetation cover, the lack of a complete Chinle section, and the absence of any reliable stratigraphic marker beds in the Chinle Formation in this area make definitive correlations uncertain. The present study included sandstone units in this part of the section either in the Agua Zarca or in the Salitral.

Salitral Shale Tongue

The contact between the Agua Zarca Sandstone Member and the overlying Salitral Shale Tongue is gradational. Sandstones of the Agua Zarca fine upward into green and gray mudstones of the Salitral. In many places, fine-grained rocks of the Salitral are poorly exposed and yield no insight as to their genesis; however, two areas of excellent exposure, at Abiquiu Dam and in the large natural amphitheatre north of Coyote, permit study of the sedimentology of the Salitral.

At Abiquiu Dam, the Salitral Shale Tongue is composed of green to gray claystones and mudstones. The green and gray claystones contain isolated lenses of fine- to medium-grained quartz sandstone that grade laterally into mottled green and purple mudstones and claystones. Locally, the mottled zone contains iron (hematite) concretions as much as 2 in. (5 cm) in

diameter. The upper part of the Salitral is composed of dark-reddish-brown, bentonitic mudstone that contains small carbonate nodules and distinctive, small cylindrical trace fossils.

The red mudstones contain singular and isolated, but commonly very abundant, carbonate nodules. The carbonate nodules are as much as 0.5 in. (1.25 cm) in diameter and increase in abundance upward. Nowhere in the red mudstones have the nodules been observed to coalesce or to have any form other than singular, isolated glaebules (Brewer, 1964, p. 259–260).

Red mudstones of the Salitral Shale Tongue exhibit ubiquitous and abundant endogenic trace fossils that are preserved in full relief (fig. 7). The trace fossils are filled with mudstone having the same composition as the surrounding matrix. The traces are sinuous and have no preferred orientation. Individual traces are cylindrical and vary in diameter from 1/16 to as much as 3/8 in. (2 mm–1.2 cm). They are nonbranching but do intersect one another. Internally, very fine, concave meniscate backfills can be observed in thin sections. The external ornamentation of the traces is expressed as fine striations parallel with the long axis of the burrow. The striations are commonly covered with a thin clay film. Slickensides are developed on the surface of parallelepiped-shaped, fist-sized blocks into which the mudstone breaks. The shape and size of the blocks is in part determined by the distribution of 2- to 3-ft- (1-m) long curvilinear, slickensided fractures that become horizontally tangential with depth. These fractures are confined to the mudstone and do not extend into overlying or underlying beds.

Figure 7. *Scoyenia* burrows (arrows) in uppermost red mudstones of Salitral Shale Tongue at Abiquiu Dam.

Isolated sandstone beds in the Salitral Shale Tongue are interpreted as fluvial deposits based on their fine to medium grain size and their lenticular geometry. Laterally equivalent purple- and white-mottled siltstones and mudstones are interpreted as levee and overbank deposits of the fluvial systems. The fine-grained mudstones represent quiet-water deposits laid down in small marshes or lacustrine basins adjacent to the fluvial systems. The superimposed mottles are thought to represent gleyed paleosols formed on the levee and fluvial units as a result of fluctuating water tables in a manner similar to that previously described for the Agua Zarca gleyed paleosols.

The red, massive mudstones at the top of the Salitral Shale Tongue are interpreted as overbank floodplain deposits. The red floodplain deposits are also paleosols, but the lack of large mottles, the finer grain size of the strata, and the red coloration indicate these paleosols formed under different conditions. The fine grain size, the isolated carbonate glaebules, and the curvilinear fractures suggest that these paleosols represent carbonate-rich vertisols (Buringh, 1968; Mohr and others, 1972; U.S. Dept. Agriculture, 1975; Young, 1976; Blodgett, 1985a, b). These vertisols were the source of the carbonate nodules, described in the next section, that occur in conglomeratic sandstones of the overlying Poleo Sandstone Lentil.

The trace fossil ichnogenus *Scoyenia* (Häntzschel, 1975) is common in continental "red bed" facies (Basan, 1978; Ekdale and others, 1984). The detail of preservation (fig. 7) of external ornamentation on the Salitral Shale Tongue traces is due to the fine grain size of the mudstone. The internal meniscate fill observed in thin sections of the burrows and the external ornamentation suggest that they can be identified as *Scoyenia gracilis* White 1929 (Frey and others, 1984). *Scoyenia* has been interpreted as the trace of a sediment-ingesting arthropod (Frey and others, 1984).

North of Coyote, the Salitral Shale Tongue is made up of a more complex array of lithofacies. At this locality, the Agua Zarca is overlain by a green sandy siltstone and silty sandstone facies. The green sandy siltstones contain abundant, finely comminuted organic carbon fragments. The green silty sandstones have abundant muscovite flakes on bedding planes. The green sandstones contain numerous medium-bedded, fine-grained beds that exhibit small-scale trough cross-stratification. Some thin-bedded, fine-grained sandstones are composed entirely of asymmetric climbing-ripple cross-stratification. The green sandstones are overlain by dark-reddish-purple, bentonitic mudstones.

The Salitral Shale Tongue is interpreted as superposed fluvial crevasse splays and small lacustrine-delta crevasse splays and lobes. This interpretation is based on lithology, sedimentary structures, overall geometry,

color, and general similarity to the green sandy facies of the Monitor Butte Member in southeastern Utah (Dubiel, 1987a). The green color of these beds is thought to reflect subaqueous deposition of clastic grains and organic carbon fragments and plant debris. Rapid subaqueous burial and inclusion of organic matter inhibited any subsequent development of diagenetic hematite that would color the beds red. Similar lithofacies associations from the Upper Carboniferous in England have been interpreted as fluvial and lacustrine crevasse splays (Fielding, 1984; Haszeldine, 1984).

The upward succession of fluvial Agua Zarca, fluvial sandstone member, fluvial-marsh Salitral, and marsh and lacustrine Salitral deposits and the gleyed paleosols within these units indicate that this part of the Chinle was deposited under conditions of continually rising, shallow water tables that were marked by seasonal fluctuations.

Poleo Sandstone Lentil

The Poleo Sandstone Lentil consists of brown to gray, medium-grained quartz sandstone, chert-granule and carbonate-nodule conglomerate, and minor mudstone lenses. Near Abiquiu Dam, the Poleo is composed of two distinct parts that can be recognized by differences in texture and sedimentary structures. The lower part is characterized by conglomeratic quartz sandstone that contains abundant red and orange chert granules (fig. 8). Sedimentary structures in the lower part include abundant tabular-planar cross-beds. The upper part is composed of white to brown, medium-grained quartz sandstone that exhibits medium- to large-scale trough cross-stratification. Internally, the entire Poleo (fig. 9) is composed of stacked, multistoried sandstone bodies (Friend, 1983). Individual sandstone bodies are lenticular and exhibit internal scour surfaces and cut-and-fill structures. The Poleo generally overlies the Salitral. Downstream from Abiquiu Dam, the Salitral Shale Tongue is absent and the Poleo overlies the Agua Zarca Sandstone Member.

The assemblage of lithology and sedimentary structures in the Poleo Sandstone Lentil indicates deposition by fluvial processes. The lenticular, coarse-grained, granular deposits and the sedimentary structures in the lower part represent bedload deposition on transverse bars in braided fluvial channels. The upper part represents bedload to mixed-load deposition of sinuous-crested dunes in more sinuous fluvial systems.

Regionally, the Poleo Sandstone Lentil thins southward from Abiquiu Dam to San Ysidro and northwest along the Rio Chama toward Coyote. The regional southward thinning from Abiquiu Dam has been documented by Kurtz (1978). Paleoflow, as determined from channel trends, trough cross-stratification, and previous studies (Stewart and others, 1972a; Kurtz, 1978), was to the west, southwest, and northwest.

Figure 8. Poleo Sandstone Lentil at Abiquiu Dam showing granular chert clasts in conglomeratic lower part of member.

Figure 9. Chinle Formation at Abiquiu Dam showing Agua Zarca Sandstone Member (Tca), Salitral Shale Tongue (Tcs), and Poleo Sandstone Lentil (Tcp). Dashed line indicates location of contact uncertain. View looking north.

Petrified Forest Member

The Petrified Forest Member overlies either the Poleo Sandstone Lentil or the Salitral Shale Tongue. The Petrified Forest is composed of brown to red, medium-grained quartz sandstones; lavender to white, bentonitic and arkosic sandstones; and gray to red and purple, bentonitic mudstones. In general, the Petrified Forest Member weathers to a slope that obscures any sedimentary structures. However, near Abiquiu Dam, at Ghost Ranch, and north of Coyote, excellent exposures of the Petrified Forest allow an interpretation of the depositional environments.

At Abiquiu Dam, the Petrified Forest Member exhibits a marked change in lithology from bottom to top. The lower part of the Petrified Forest is composed of brown and red, thin- to medium-bedded quartz sandstone with trough cross-stratification and thin sandstone beds with climbing-ripple cross-stratification. This unit grades upward into muddy sandstone beds that exhibit large-scale cross-stratification. The upper part of the member is composed of poorly exposed red and purple mudstones.

At Ghost Ranch, the cross-laminated, muddy sandstone beds at Abiquiu Dam are very well exposed. The lavender to purple and white, bentonitic and arkosic, muddy sandstone beds contain thin lenses of carbonate-nodule conglomerate and typically exhibit what has been described previously as large-scale, low-angle, trough cross-stratification (Stewart and others, 1972a). The present study indicates that the Petrified Forest exhibits several styles of cross-stratification. The coarser grained sandstones and basal lag, carbonate-nodule conglomerate contain small- to medium-scale trough and tabular-planar crossbeds. The lavender sandstones are composed of interbedded arkosic sandstone and bentonitic sandstone that were deposited on larger scale scour and lateral accretion surfaces. The lavender sandstones interfinger with very thin bedded, ripple-laminated mudstones, bentonitic sandstones, and siltstones that contain abundant tetrapod remains (Colbert, 1974) and freshwater unionid bivalves (Cope, 1875).

North of Coyote, the three parts of the Petrified Forest Member are all well exposed. Overlying the Poleo Sandstone Lentil, the Petrified Forest contains several vertically stacked but slightly offset, lenticular, medium-grained sandstone beds. These sandstone beds can be traced laterally into interbedded, very thin bedded siltstones and mudstones that in turn grade laterally into red and purple mudstones. The lenticular sandstones are as thick as 30 ft (10 m). The thin-bedded siltstones display abundant climbing-ripple stratification and have a paleoflow direction generally north, perpendicular to the westward trend of the sandstone beds.

Overlying the sandstones just described are large-scale crossbedded bentonitic and arkosic sandstones similar to those at Ghost Ranch. The sandstones are commonly lavender to dark purple but are light green where they contain organic fragments. During this investigation, four phytosaur vertebrae (J.M. Parrish,

oral commun., 1986) and a single unionid bivalve (S.C. Good, oral commun., 1986) were collected from these beds. Reddish-brown and purple mudstones overlie the sandstones. The mudstones of the Petrified Forest Member are thick bedded to massive and, because of their high bentonite composition, commonly weather to rounded hills and steep slopes. Viewed from a distance (fig. 10), the mudstones exhibit alternating reddish-brown and lavender horizontal banding.

The Petrified Forest sandstones are interpreted as fluvial deposits that interfinger with fossil-bearing, low-angle trough crossbedded, fluvial crevasse-splay deposits. The splay deposits, in turn, grade laterally into floodplain mudstones with superimposed paleosol horizons. The sandstones are characterized by an abundance of low-angle, complexly crosscutting lateral accretion bedding, numerous splay deposits, and floodplain mudstones that completely encase sandstone beds. The sandstones probably were deposited by high-sinuosity streams that carried an abundant suspended-sediment load and probably were subject to numerous avulsion events. The presence of fossil riparian phytosaurs and perennial-fluvial unionids (Parrish and Good, 1987) within the fluvial crevasse-splay strata provide independent complementary evidence for low-gradient, perennial Petrified Forest fluvial systems.

The dark-red-brown paleosols in the Petrified Forest grade laterally into paleosols that exhibit more pronounced vertical horizon differentiation and development. The paleosol relationships represent increasing pedogenic modification of overbank floodplain deposits with increasing distance from the fluvial source. These more distal paleosols are characterized by light-lavender A horizons and thick, deep-reddish-brown B horizons (fig. 10). Well-developed paleosols on floodplain deposits near Coyote and abundant fluvial crevasse-splay deposits near Ghost Ranch suggest that the main fluvial system that deposited the Petrified Forest Member was to the east or southeast. The paleosols are similar to those described for the Eocene Willwood Formation in Wyoming (Bown and Kraus, 1987) and for the Chinle Formation in Petrified Forest National Park in Arizona (Kraus and Bown, 1986) and in southeastern Utah (Dubiel, 1987a). The more well developed paleosol horizons are considered to have formed farther away from the fluvial systems where there was increased time for paleosol development between flood-sedimentation events (Bown and Kraus, 1987).

Siltstone Member

The siltstone member is composed of reddish-brown to brown siltstones and very fine to fine grained quartz sandstones. The member generally weathers to a steep slope without any distinguishing characteristics. However, at Abiquiu Dam, at Echo Amphitheatre just north of Ghost Ranch, and at a locality just south of Ghost Ranch, the siltstone member is exposed well enough to discern some unusual primary sedimentary structures.

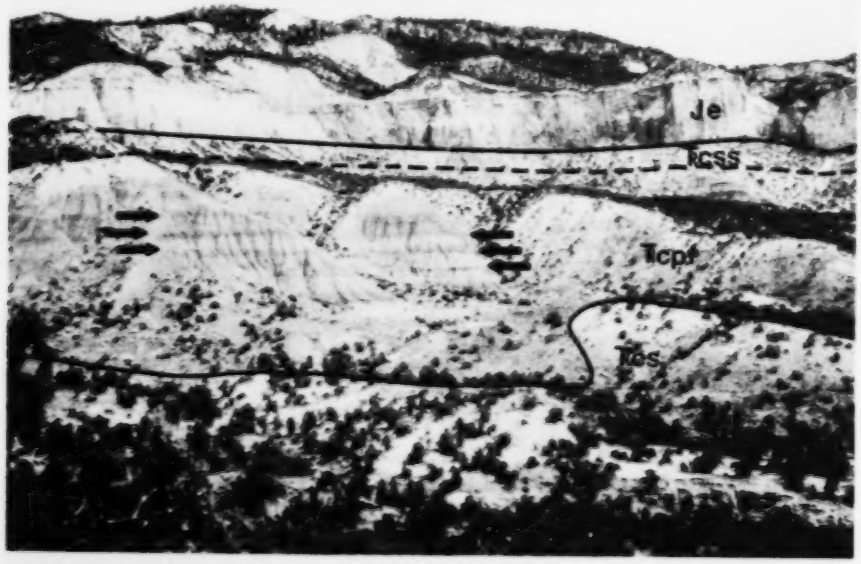

Figure 10. Petrified Forest Member north of Coyote. Mudstones of the Petrified Forest exhibit horizontal color banding (arrows) as the result of paleosol development. Petrified Forest (Trcpf), Salitral Shale Tongue (cs), and siltstone members (Trcss) of the Chinle Formation overlain by the Entrada Sandstone (Je). View looking north.

At Abiquiu Dam, the siltstone member is not completely exposed but does exhibit several very thin bedded to very thinly laminated, fine to very fine grained quartz sandstones (fig. 11). The sandstones are 10–15 ft (3–5 m) thick, and on bedding plane surfaces they contain abundant, meniscate backfilled, cylindrical trace fossils that average about 0.25–0.5 in. (1 cm) in diameter.

At Echo Amphitheatre, the siltstone member is composed of reddish-brown, medium- to thick-bedded, fine to very fine grained sandstones that appear structureless from a distance. The apparent lack of sedimentary structures is due to pervasive bioturbation that results in a knobby-weathered surface. The upper 25 ft (8.5 m) of the siltstone member directly below the Entrada Sandstone contains spectacular examples of both large and small trace fossils. The large trace fossils are as much as 4 in. (10 cm) in diameter and are as much as 4 ft (1.2 m) long (fig. 12). The large cylindrical traces are vertical and sinuous and commonly are white in contrast to the enclosing reddish-brown matrix. Between the large trace fossils are abundant ⅛–3/16 in. (3–5 mm) diameter, vertical and horizontal, sinuous trace fossils. Weathered surfaces and polished slabs (fig. 13) exhibit several varieties of endogenic, actively filled trace fossils including *Skolithos*, *Muensteria* (Häntszchel, 1975; Bracken and Picard, 1984), and other indeterminate traces.

Trace fossils identical to the large, cylindrical trace fossils in the siltstone member occur elsewhere in other members of the Chinle Formation and are interpreted as passively filled casts of lungfish burrows (Dubiel and others, 1987). The morphology and dispersion of the trace fossils at Echo Amphitheatre are similar to other Chinle lungfish burrows and are similarly interpreted. The smaller diameter trace fossils are probably the product of infaunal, sediment-ingesting invertebrates; this interpretation is based on the morphology, size, and dispersion of the traces and comparisons to previously published descriptions of similar structures (Basan, 1978; Bracken and Picard, 1984; Ekdale and others, 1984). The knobby-weathered texture of the rocks results from destruction of primary sedimentary structures by extensive bioturbation.

South of Ghost Ranch, the siltstone member is composed of reddish-brown, thin- to thick-bedded, very fine grained sandstone and siltstone (fig. 14). The horizontal beds are laterally extensive but locally show scours filled with large-scale crossbedded siltstone. Individual beds are successively truncated by the overlying unconformable contact with the Entrada Sandstone. The uppermost siltstone beds of the Chinle locally contain desiccation cracks as much as 2 in. (5 cm) across and as much as 1 ft (0.3 m) wide that are filled with sandstone of the overlying Entrada.

The large cylindrical trace fossils interpreted to be lungfish burrows are ubiquitous at this outcrop (figs. 15, 16) and have obliterated any original sedimentary structures. Locally, the burrows increase in abundance upward in individual beds, and, at the top of the beds, the superimposed bioturbation episodes have obliterated individual burrows. In the matrix between individual lungfish burrows, the siltstone is bioturbated on a smaller

Figure 11. Siltstone member near Abiquiu Dam showing laminated siltstone bed deposited in a marginal lacustrine environment. Hammer shown for scale.

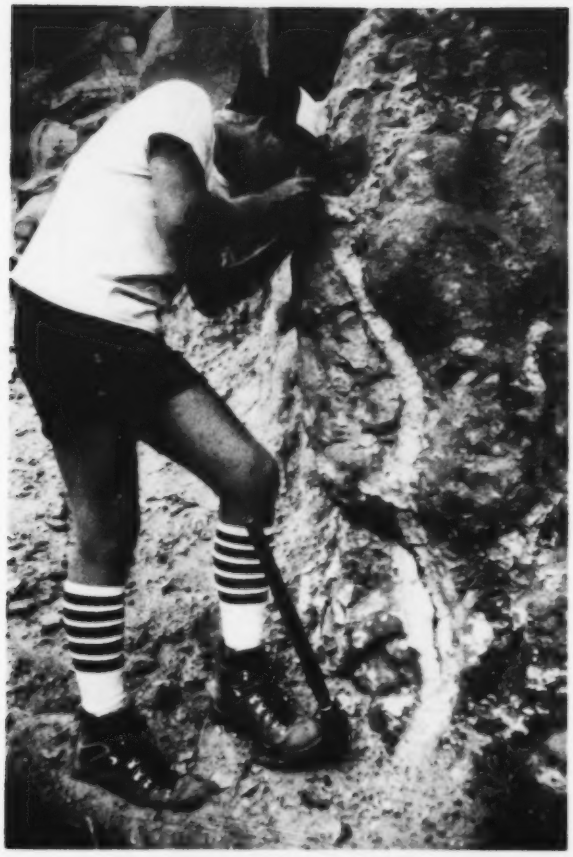

Figure 12. Siltstone member at Echo Amphitheatre, just north of Ghost Ranch. Large, cylindrical trace fossils are interpreted as casts of lungfish burrows.

scale and displays abundant, crosscutting examples of *Muensteria* and *Skolithos* similar to those at Echo Amphitheatre.

An interpretation of the depositional environments of the siltstone member is enigmatic because of the general lack of sedimentary structures, a lack due in part to the intense bioturbation and in part to the poor exposures. The burrows and bioturbation, however, can be considered as primary biogenic sedimentary structures (Howard, 1978). In addition, consideration of the large-scale facies changes in the Chinle Formation on the Colorado Plateau helps provide insight into the depositional environments of the siltstone member.

The fine grain size and laterally extensive, horizontally bedded siltstones and sandstones imply low-energy depositional environments. If the large trace fossils are lungfish burrows, then that environment must have contained enough standing water to support a fish population. The abundance of actively filled, meniscate trace fossils formed by sediment-ingesting invertebrates indicates that the sediment contained detrital organic matter. The inferred presence of organic carbon in the sediments supports the interpretation that the water table was shallow and that the sediment was probably wet, although it may have been subaerially exposed.

A depositional reconstruction of the Chinle Formation in the Four Corners area places the lacustrine basinal limestones and marginal lacustrine siltstones of the Owl Rock Member of the Chinle Formation above the Petrified Forest Member (Stewart and others, 1972a; Blakey and Gubitosa, 1983: Dubiel, 1983b, 1987a). If the Petrified Forest Member of the eastern San Juan basin correlates only with the Petrified Forest Member of northern Arizona and southern Utah, as determined during the present investigation, then the siltstone member and perhaps the uppermost part of the Petrified Forest Member in the eastern San Juan basin are lateral equivalents and lateral facies of the Owl Rock Member lacustrine strata. The siltstone member would represent strata deposited on the margins of a large lacustrine basin as represented by the Owl Rock Member, a basin that underwent episodic expansions and contractions (Dubiel, 1987a). The siltstone member contains primary physical and biogenic sedimentary structures indicative of subaqueous deposition.

The lithology and grain size of the strata, bedding, trace fossil assemblages, and regional facies relationships indicate that the siltstone member was deposited in a quiet-water environment. This environment is interpreted as lateral to the Owl Rock Member basinal lacustrine deposits recognized in the Four Corners area by Dubiel (1987a). The siltstone member is interpreted to have been deposited in a marginal lacustrine setting on periodically flooded and exposed lacustrine mudflats (see Hubert and Hyde, 1982). The laterally restricted cut-and-fill features in the siltstone member are interpreted as deposits of small streams that traversed the marginal lacustrine deposits in times of low lake levels.

DEPOSITIONAL SYNTHESIS

Lithofacies, paleocurrent data, paleontologic information, paleosols, trace fossils, and additional measured sections from studies of the Chinle Formation on the Colorado Plateau were incorporated into lithofacies assemblages to interpret Chinle depositional environments and history.

The schematic representation of Chinle deposition (fig. 17) depicts the assemblage of lithofacies interpreted herein as a complex fluvial-lacustrine system that experienced expansions and regressions of marsh and lacustrine environments. Associated fluvial systems prograded into the Chinle depositional basin. The fluvial deposition of both the Agua Zarca and the sandstone member to the west initially filled the lowest parts of paleovalleys incised into Permian rocks and in time progressed up

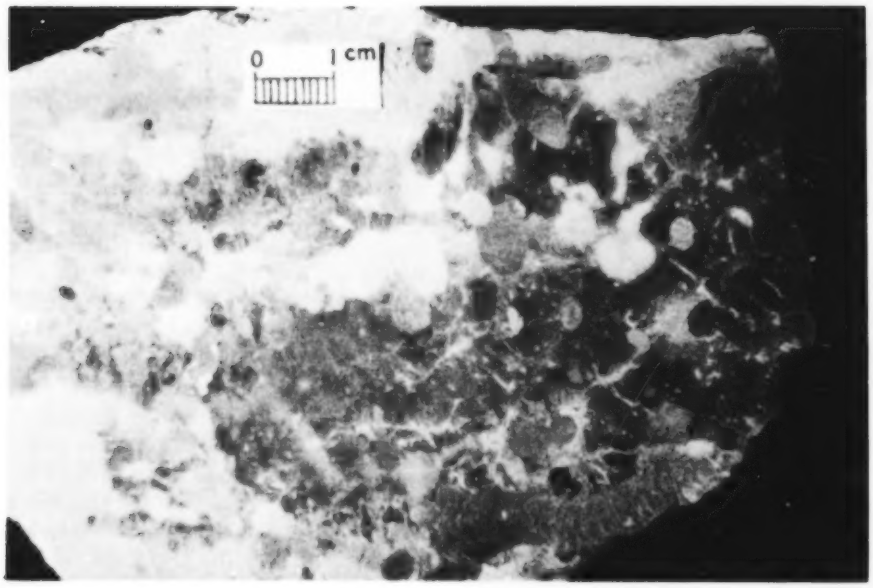

Figure 13. Abundant examples of *Skolithos* and *Muensteria* trace fossils in polished hand sample of the siltstone member collected at Echo Amphitheatre, just north of Ghost Ranch. These trace fossils are actively filled, meniscate traces of probable sediment-ingesting arthropods.

Figure 14. Laterally extensive horizontal bedding typical of the siltstone member at locality south of Ghost Ranch. Je, Entrada Sandstone. Geologist above arrow.

valley in response to rising base levels. As headward deposition proceeded up paleovalleys, erosion of underlying Permian and older strata progressed up valley in the drainage basin.

The gleyed paleosols of the Agua Zarca Sandstone Member and Salitral Shale Tongue and the associated wetland marsh, bog, and fluvial-lacustrine splay deposits of the Salitral represent deposition at or near the local base level. Seasonal flooding of fluvial and floodplain deposits is indicated by the ubiquitous gleyed paleosols. Thin lacustrine carbonates (Chenoweth, 1974) and mudstones of the Salitral were deposited in small lakes.

Figure 15. Closeup view of the siltstone member south of Ghost Ranch. Detailed view of cliff with geologist in same position as in figure 14. Large trace fossils are interpreted to be lungfish burrows.

An increase in volcaniclastic sedimentation, probably associated with either an increase in volcanic activity in the magmatic arc that existed to the west of the Triassic continent (Dickinson, 1981), or an increase in clastic sedimentation associated with the Ancestral Rocky Mountain and Uncompaghre Highlands to the north and northeast of the San Juan basin (Stewart and others, 1972a; Kurtz, 1978) resulted in the generally westward progradation of the Salitral Shale Tongue and Poleo Sandstone Lentil fluvial and crevasse-splay systems. At this time, the remnant paleovalleys that had been eroded into the Cutler Formation were essentially filled with sediment, producing a flat depositional plain.

The sinuous, meandering fluvial channels, splays, and floodplains of the Petrified Forest Member prograded westward over the Salitral Shale Tongue and Poleo Sandstone Lentil. The development of thick vertic paleosols on floodplain mudstones of the Petrified Forest fluvial-overbank deposits attests to long periods of time between depositional flood events and supports an interpretation of seasonal precipitation and flooding. The occurrence of fossils of terrestrial vertebrates (Colbert, 1974) indicates that dry land existed (Parrish and Long, 1983), but the occurrences of fossils of aquatic phytosaurs and fluvial unionids indicates that water tables were shallow and often at the surface.

Owl Rock Member lacustrine carbonate rocks and siltstones were deposited in a large lacustrine basin that existed in the Four Corners area and that extended at least as far southeast as Prewitt, N. Mex. (fig. 1) (Stewart and others, 1972a, pl. 2; Dubiel, 1987a). Owl Rock micritic limestones were deposited as basinal lacustrine or marsh strata, and siltstones and fine sandstones were deposited on the lake margins.

Lateral to the Owl Rock lacustrine deposits, the siltstones and fine-grained sandstones of the siltstone member of the Chinle were deposited on lacustrine and exposed mudflats in the eastern San Juan basin. The presence of abundant lungfish burrows and extensive small burrows and bioturbation suggest periodic fluctuations in the level of the lake and corresponding transgressions and regressions of the lake shore.

Uppermost Chinle strata either were removed or were never deposited prior to the deposition of the Entrada Sandstone, and the regional nature of the angular unconformity makes statements about any missing upper Chinle beds speculative.

PALEOCLIMATE

Although a certain degree of consensus exists as to the interpretation of continental depositional environments and the history of the Chinle Formation (Stewart and others, 1972a; Lupe, 1979; Blakey and Gubitosa, 1983; Dubiel, 1983b, 1987a, b), a lack of agreement persists regarding the interpretation of the climate that prevailed at the time of Chinle deposition. Climatic interpretations based on a variety of stratigraphic and paleontologic evidence range from arid and semiarid climate (Stewart and others, 1972a) with through-flowing streams (Daugherty, 1941), to a humid tropical climate (Ash, 1967, 1972, 1978; Gottesfeld, 1972), and to one with progressively increasing aridity (Blakey and Gubitosa, 1983). Recent sedimentologic and paleontologic studies in Petrified Forest National Park, Ariz. (Bown and others, 1983), and in southeastern Utah (Dubiel, 1983b, 1984, 1986, 1987a, b; Good and others, 1987; Parrish and Good, 1987) characterize the Late Triassic climate as wet but punctuated by seasonally dry periods.

Several lines of sedimentologic evidence discussed in the preceding sections bear on the intepretation of climate at the time of Chinle deposition: (1) lithofacies variation and interpretation of depositional environments; (2) vertical succession of depositional environ-

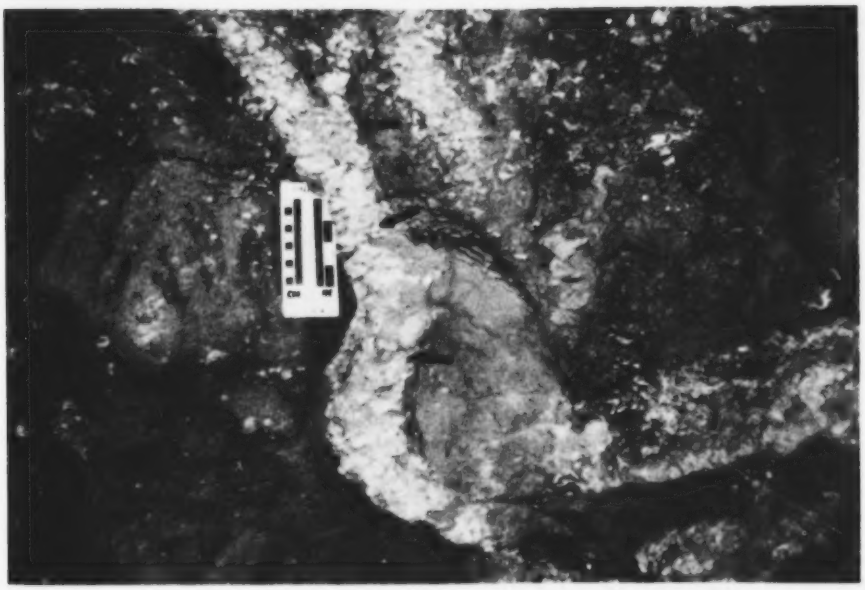

Figure 16. Detailed view of a lungfish burrow shown in figure 15. Arrows point to small trace fossils superimposed on the lungfish burrows.

ments as a reflection of fluctuating water tables; (3) occurrence of lungfish burrows and gleyed paleosols in several depositional environments and occurrence of lungfish burrows in the uppermost Chinle strata; (4) distribution and character of faunal assemblages and trace fossils; (5) paleosols developed on fluvial floodplain, and exposed mudflat deposits as an indication of frequency and abundance of precipitation; (6) variation in organic-matter content and associated color of the rocks as a reflection of water table at the time of deposition; and (7) considerations based on the paleontology of vertebrates, invertebrates, and plants.

The vertical succession of lithofacies and their interpreted depositional environments reflect a depositional model characterized by fluvial, deltaic, and lacustrine systems. The progression from fluvial systems of the Agua Zarca and the sandstone member to marsh, lacustrine, and deltaic systems of the Salitral Shale Tongue and fluvial systems of the Poleo Sandstone Lentil points to the development of a lake by expansion and its subsequent demise due to filling by progradation of clastic systems. The overlying succession of fluvial and floodplain Petrified Forest systems to lacustrine Owl Rock and lacustrine-mudflat siltstone member systems indicates the development and filling of a second lacustrine system. These large-scale trends were controlled by rate and locus of tectonic subsidence, rate of sediment supply from tectonic and volcanic sources, and amount and seasonal distribution of precipitation as a reflection of long-term climate.

The abundance of fluvial, marsh, and lacustrine environments indicates abundant water in the depositional system and water tables that persisted near or above the ground surface much of the time. The gleyed paleosols and the lungfish burrows indicate that there was seasonal flooding and fluctuation of these water tables within the sediments. The occurrence of lungfish burrows up into the siltstone member demonstrates that the climate was sufficiently wet and stable to support lungfish in extensive lacustrine and marsh habitats throughout deposition of the upper Chinle

Fossil vertebrates, invertebrates, and plants in related Chinle strata on the Colorado Plateau (Dubiel, 1983b, 1984, 1987a, b) afford independent and complementary interpretations of depositional environments and paleoclimate of the enclosing rocks (Good and others, 1987; Parrish and Good, 1987). The inferred habitats of metoposaur amphibians and phytosaur reptiles (Colbert, 1974) support interpretations of extensive aquatic environments that must have been perennial. The perennial nature of fluvial systems in the Moss Back Member of the Chinle Formation is suggested by the occurrence of thick-shelled, nonaestivating unionids in Moss Back crevasse-splay deposits (Good and others, 1987). Paleobotanical evidence is interpreted to indicate wet or humid tropical conditions (Ash, 1972, 1978; Gottesfeld, 1972) during Chinle deposition. Aside from the actual paleobotanical interpretations of the plants, their preservation as

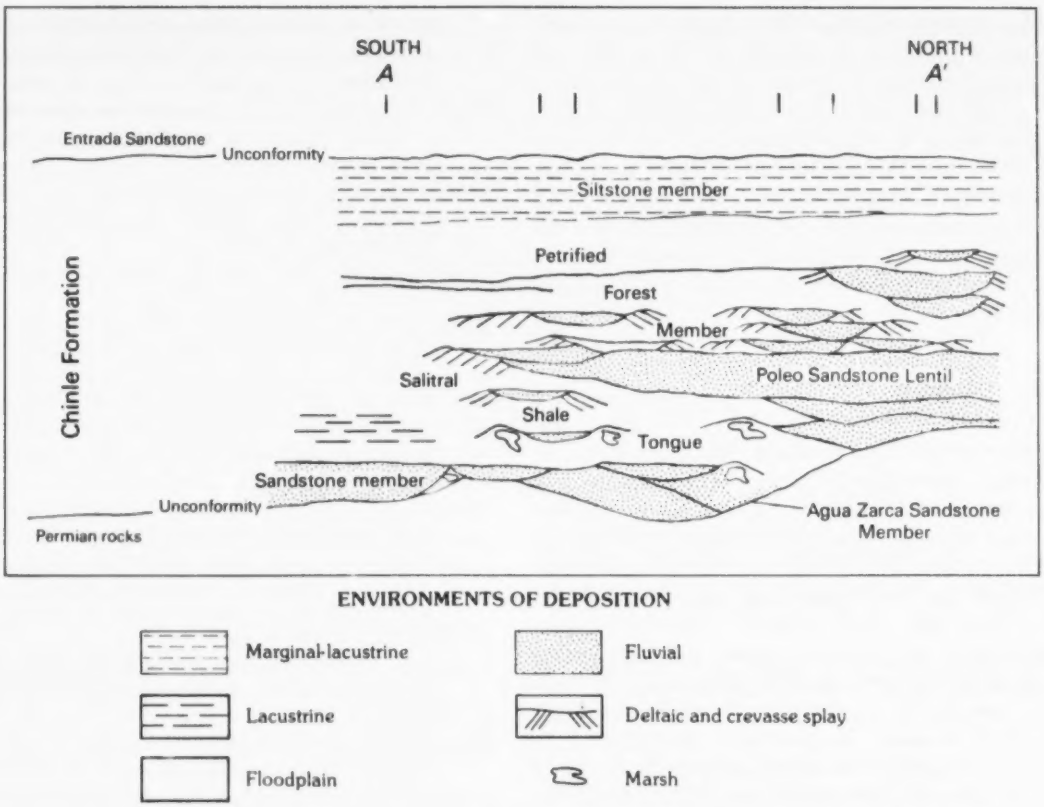

Figure 17. Schematic panel showing interpreted environments of deposition for the Chinle Formation, eastern San Juan basin, along line of section *A–A'* (shown in figure 3). Constructed using information from figure 3, additional data from observed unmeasured sections, and information obtained by tracing out beds. Short vertical lines at top indicate locations of measured sections used to compile line of section *A–A'*.

carbonized remains and sediment-filled pith casts indicates conditions of rapid subaqueous burial.

Finally, the rock colors, which are a reflection of present hematite content and are thought to reflect the original organic content and the paleosol development, yield additional insight into water table fluctuations and climate. The gray, black, and green rocks of the Salitral Shale Tongue reflect high organic-carbon content that was the result of rapid sedimentation and preservation in subaqueous environments below the water table, away from the oxidizing effects of the atmosphere. Well-developed paleosols would not be expected in these subaqueous environments; however, seasonally exposed floodplains or lacustrine mudflats would be expected to display some effects of pedogenesis. The color mottling in the purple-mottled units is thought to reflect alternating reducing and oxidizing conditions in the presence of organic matter. The redox conditions reflect fluctuating water tables in the environment. The development of singular, isolated carbonate nodules in Chinle vertisols probably reflects the seasonal influx of carbonate provided by precipitation or overbank flooding.

The Petrified Forest Member is lavender within fluvial channel and splay deposits and deeper red in floodplain deposits. The color variation reflects the more variable water tables of environments that were subjected to seasonal flooding but not to extensive subaqueous conditions. The development of hematite in these rocks is due to the lack of carbon, and the rocks are a deeper red because of deposition under more oxidizing conditions due to periodic subaerial exposure. Deposition on subaerially exposed mudflats and beneath oxygenated marginal-lacustrine waters resulted in the red coloration of the siltstone member.

Early in the history of Chinle deposition, water was abundant in the depositional system. Marsh wetland, lacustrine basin and mudflat, and fluvial and floodplain environments supported aquatic and terrestrial faunas and floras. During deposition of the uppermost members of the Chinle, large lakes and episodically exposed mudflats characterized the Chinle depositional systems.

The identified depositional environments and their superimposed vertisol and gleyed paleosols suggest that

water was relatively abundant in the depositional system, but fluctuating water tables indicate seasonally dry periods with lower water tables. Paleomagnetic reconstructions place this part of the Colorado Plateau within the tropics during the Late Triassic (Van der Voo and others, 1976), and the climate can be characterized as tropical monsoonal. This interpretation is consistent with independent evidence from paleontology (Parrish and Long, 1983), palcobotany (Ash, 1972; Gottesfeld, 1972), and paleoclimatic models (Robinson, 1971; Parrish and others, 1986).

CONCLUSIONS

The Upper Triassic Chinle Formation in the eastern San Juan basin and vicinity was deposited in a complex fluvial-deltaic-lacustrine system in which lakes experienced episodic fluctuations in size. Lithofacies variability is a direct result of the numerous depositional environments and subenvironments that existed in the system. Fluvial and deltaic deposits of the Aqua Zarca, Salitral, Poleo, and Petrified Forest were deposited generally to the west and marginal lacustrine beds of the siltstone member were deposited on the eastward margin of the Owl Rock lacustrine system.

Deposits of this fluvial-deltaic-lacustrine system supported a diverse invertebrate and vertebrate fauna. Fossils in the Chinle provide important evidence to substantiate depositional environments, paleoclimate, and paleoecology. Aquatic and terrestrial fossil assemblages support sedimentologic interpretations of Chinle depositional environments. Evidence from sedimentology, macrofossils, trace fossils, and paleosols indicates that the Chinle paleoclimate was tropical monsoonal and provided sufficient moisture to form streams, marshes, and lakes, but that it was punctuated by seasonally dry periods.

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Chapter C

Trace Fossils and Mollusks from the Upper Member of the Wanakah Formation, Chama Basin, New Mexico: Evidence for a Lacustrine Origin

By JENNIE L. RIDGLEY

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

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CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C = (temp °F–32)/1.8

Trace Fossils and Mollusks from the Upper Member of the Wanakah Formation, Chama Basin, New Mexico: Evidence for a Lacustrine Origin

By Jennie L. Ridgley

Abstract

The trace fossils, *Rhizocorallium*, *Thalassinoides*, and *Arenicolites*, and a nonmarine mollusk, *Vetulonaia* sp., have been found in the upper member of the Middle Jurassic (middle and upper Callovian) Wanakah Formation at a number of localities in the southern part of the Chama basin, New Mexico. In this area, the upper member of the Wanakah Formation, previously called the Summerville Formation, occurs below the nonmarine Morrison Formation and above the Todilto Limestone Member of the Wanakah, which is reported to be of marine or lacustrine origin. The entire Wanakah Formation of the Chama basin is considered to be correlative to the Curtis and Summerville Formations of Utah and to the Pine Butte Member of the Sundance Formation of Wyoming and northern part of Colorado.

The assemblage of trace fossils from the upper member of the Wanakah would normally indicate that a marine incursion occurred in this area during the Callovian; however, the presence of the nonmarine mollusk in strata underlying strata containing the trace fossils indicates a lacustrine depositional setting for the upper member of the Wanakah. Trace fossils similar to those in the Wanakah have been reported from Triassic lacustrine rocks in Greenland. The trace fossils and mollusks in the upper Wanakah are found in rocks characteristic of deposition in shallow lacustrine nearshore environments.

INTRODUCTION

The sedimentology, paleoenvironments, and paleogeographic distribution of the upper member of the Middle Jurassic (Callovian) Wanakah Formation of southern Colorado and northern New Mexico are poorly known. Middle Jurassic paleoenvironmental reconstructions (Harshbarger and others, 1957; Peterson, 1972; Ridgley, 1977; Imlay, 1980; Brenner, 1983; Kocurek and Dott, 1983) suggest that the Wanakah (Summerville of many reports) is of marine, marginal-marine, or continental origin. Prior to this report, however, no conclusive evidence for a specific environment of deposition had been offered.

Recent studies of the upper member of the Wanakah Formation in the southern part of the Chama basin of north-central New Mexico (fig. 1) recognize three types of trace fossils and one type of nonmarine mollusk; trace fossils and mollusks were not previously reported from the Wanakah Formation in this area. This report describes the type and distribution of the trace fossils and mollusk and discusses their significance as paleoenvironmental indicators used to extend and refine our knowledge of the paleoenvironments of the southern part of the Colorado Plateau during Middle Jurassic time. The trace fossils and mollusk indicate a lacustrine depositional setting for the upper member of the Wanakah Formation in the Chama basin.

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STRATIGRAPHY

The Wanakah Formation in south-central Colorado, as described by Goldman and Spencer (1941), is a carbonate, evaporite (caicium sulfate), and clastic

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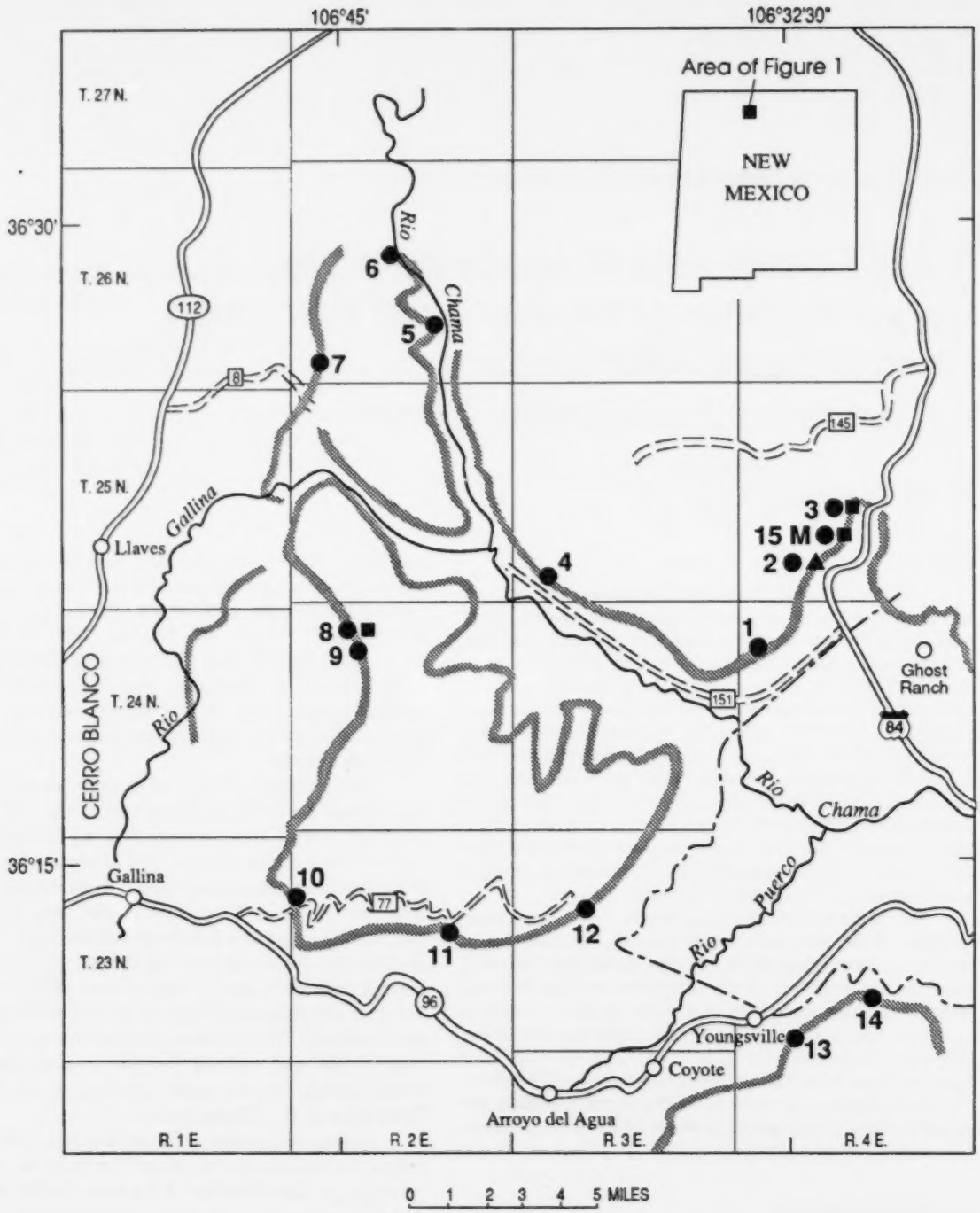


Figure 1. Location of study area, approximate outcrop distribution of the Wanakah Formation (patterned area; width not to scale), and trace fossil and nonmarine mollusk localities in the southern part of the Chama basin, New Mexico. Fossil localities: circle, *Rhizocorallium* sp.; triangle, *Thalassinoides* sp.; square, *Arenicolites curvatus*; M, *Vetulonaia*.

sequence that has been divided into three members. The basal member, the Pony Express Limestone, consists of limestone and gypsum; the middle member, the Bilk Creek Sandstone, consists entirely of sandstone; and the upper member, formerly referred to as the marl member, consists of interbedded sandstone, siltstone, mudstone, and, locally, limestone. In the Chama basin of north-central New Mexico, the equivalent of the Pony Express Limestone Member is the Todilto Limestone Member; equivalents of the Bilk Creek and upper members of the Wanakah have not been subdivided and are referred to as the upper member. The upper member may also be equivalent to the Beclabito and Horse Mesa Members of the Wanakah in eastern Arizona (Condon and Huffman, 1988), but regional correlations showing equivalency have not been done. Figure 2 summarizes regional differences in nomenclature subdivision of the Wanakah Formation.

The undivided upper member of the Wanakah Formation previously was considered to be equivalent to the Summerville Formation (Craig and others, 1959; Ridgley, 1977), and the names were used interchangeably, or it was included in the Morrison Formation (Smith and others, 1961) for the purposes of mapping. Recently, however, Pipiringos and O'Sullivan (1978) and O'Sullivan (1980, 1986) demonstrated that the type Summerville is in part younger than the Wanakah and that the Summerville is truncated beneath the J–5 unconformity at the base of the Morrison Formation in eastern Utah and thus probably does not extend into southwestern Colorado. The Summerville in Utah and the Wanakah in Utah and New Mexico are in part laterally time equivalent. Condon and Huffman (1988) proposed that use of the name Summerville in New Mexico be dropped. The name Summerville is no longer valid in the Chama basin (Pipiringos and O'Sullivan, 1978; O'Sullivan, 1980, 1986); instead, the stratigraphic sequence of this report is related to the Wanakah of southern Colorado. As defined in this report, the Wanakah Formation in the Chama basin includes the basal Todilto Limestone Member and an unnamed clastic member that is overlain by the Morrison Formation. In the Chama basin, the upper member conformably overlies the Todilto Limestone Member and is conformably overlain by the Morrison Formation. The J–5 unconformity (Pipiringos and O'Sullivan, 1978; O'Sullivan, 1986) that marks the contact between the Morrison and Wanakah Formations in western Colorado is not recognized in the Chama basin.

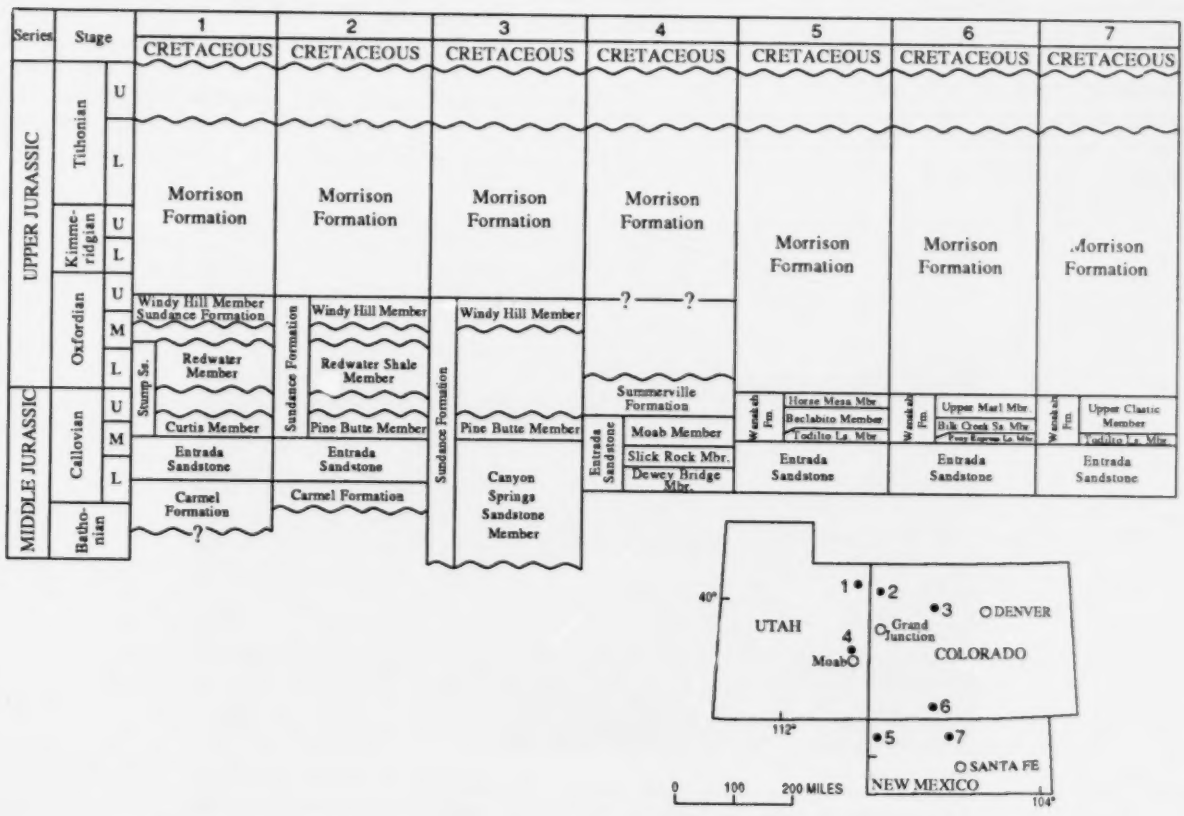


Figure 2. Variations in nomenclature within the Wanakah Formation in Colorado, New Mexico, and Utah.

SEDIMENTOLOGY

The upper member of the Wanakah Formation in the southern part of the Chama basin (figs. 3, 4) may be as thick as 55 ft (17 m). It consists of a basal diamictite that contains angular clasts of limestone, sandstone, or quartzite in a sandstone matrix, a middle sequence of predominantly sandstone and lesser amounts of mudstone or siltstone, and an upper sequence of thick- and thin-bedded, ripple-laminated sandstone and local thin beds of gray, grayish-green, or reddish-brown sandy mudstone or gray shale (fig. 4) and gray limestone. Mudstone beds vary in thickness and abundance from one locality to another. The sandstone is characteristically very fine to fine grained; coarse- and medium-grained sandstone is present locally, especially near the top of the member. Fine-grained sandstone locally contains sparse amounts of medium and coarse grains. Sandstone is dominantly well sorted and subrounded and contains a few percent feldspar. Calcite is the principal cement; anhydrite mixed with calcite and barite cement is locally present, especially in the lower sandstone beds.

The basal diamictite is of variable thickness and exhibits no distinct sedimentary structures. Clasts within the diamictite range in size from 1 in. (2.5 cm) to more than a foot (0.3 m) in diameter; their distribution is both normally and inversely graded (fig. 5*A*). The fabric of the diamictite varies laterally and vertically from clast supported to more commonly matrix supported, the matrix being sandstone. Locally, an anastomosing network of sandstone-filled fractures crosscuts the diamictite or the sandstone unit that overlies the diamictite unit.

Thick sandstone beds above the basal diamictite have flat to undulatory bases and locally exhibit discontinuous-even and wavy-parallel laminations or indistinct to well-defined trough and tabular cross-stratification. At several localities in the middle part of the upper member of the Wanakah, a persistent sandstone interval contains soft-sediment deformation structures (fig. 5*B*), including bulbous protrusions along the base of the sandstone interval (fig. 5*C*). The bulbous protrusions of sandstone into underlying mudstone partings are interpreted as the incipient formation of ball-and-pillow structures. Similar structures form subaqueously during rapid sedimentation in both shallow- and deep-water environments (Reineck and Singh, 1975). Red, green, or gray mudstone beds commonly separate thick sandstone intervals. The mudstone is arenaceous and calcareous and becomes more dominant towards the central part of the depositional basin.

Sandstone in the upper part of the upper member is commonly thin bedded and has a hummocky base. Well-developed asymmetric or oscillation ripples commonly occur at the top of beds (fig. 6*F*). Near the top of the formation, interference ripples locally have also been observed (fig. 5*D*). Red, green, or gray mudstone beds are interbedded with the thin sandstone beds. Locally, a gray limestone bed is found at the contact between the Wanakah and Morrison Formations. This limestone bed is laterally discontinuous and may contain as yet unidentified ostracodes and charaphytes.

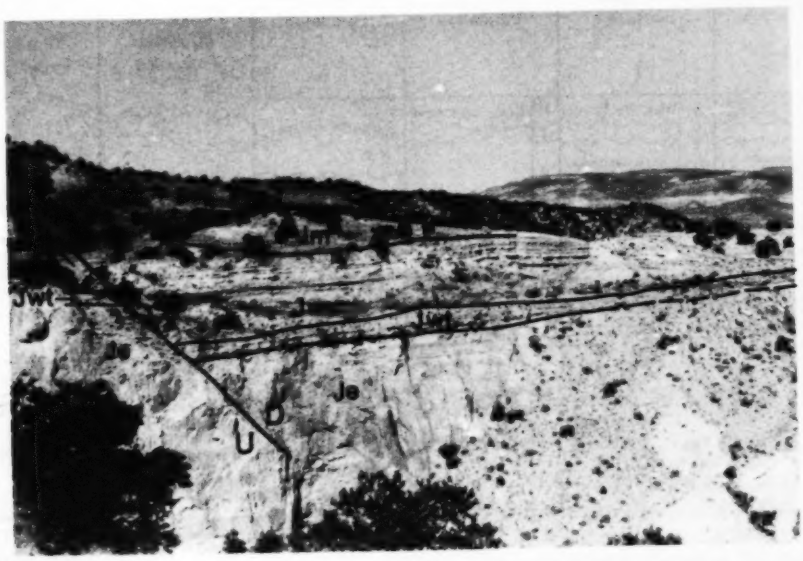
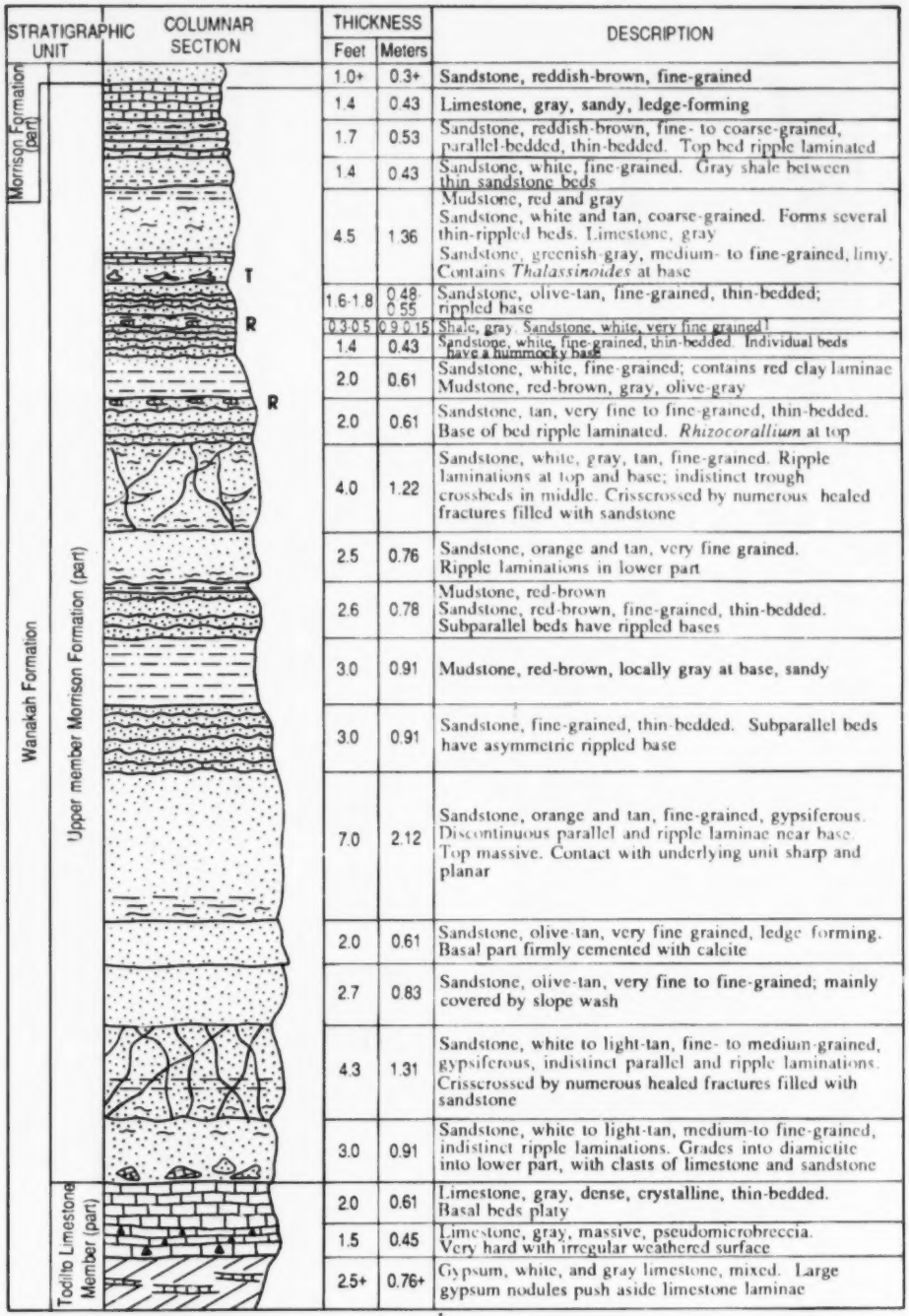


Figure 3. An outcrop of the upper member of the Wanakah Formation (Jwu) east of Youngsville, N. Mex. (fig. 1, loc. 14). Underlying Todilto Limestone Member (Jwt) and Entrada Sandstone (Je) and overlying Morrison Formation (Jm) are partly exposed.



THICKNESS		DESCRIPTION
Feet	Meters	
1.0+	0.3+	Sandstone, reddish-brown, fine-grained
1.4	0.43	Limestone, gray, sandy, ledge-forming
1.7	0.53	Sandstone, reddish-brown, fine- to coarse-grained, parallel-bedded, thin-bedded. Top bed ripple laminated
1.4	0.43	Sandstone, white, fine-grained. Gray shale between thin sandstone beds
4.5	1.36	Mudstone, red and gray Sandstone, white and tan, coarse-grained. Forms several thin-rippled beds. Limestone, gray Sandstone, greenish-gray, medium- to fine-grained, limy. Contains *Thalassinoides* at base
1.6-1.8	0.48-0.55	Sandstone, olive-tan, fine-grained, thin-bedded; rippled base
0.3-0.5	0.9-0.15	Shale, gray. Sandstone, white, very fine grained[1]
1.4	0.43	Sandstone, white, fine-grained, thin-bedded. Individual beds have a hummocky base
2.0	0.61	Sandstone, white, fine-grained; contains red clay laminae Mudstone, red-brown, gray, olive-gray
2.0	0.61	Sandstone, tan, very fine to fine-grained, thin-bedded. Base of bed ripple laminated. *Rhizocorallium* at top
4.0	1.22	Sandstone, white, gray, tan, fine-grained. Ripple laminations at top and base; indistinct trough crossbeds in middle. Crisscrossed by numerous healed fractures filled with sandstone
2.5	0.76	Sandstone, orange and tan, very fine grained. Ripple laminations in lower part
2.6	0.78	Mudstone, red-brown Sandstone, red-brown, fine-grained, thin-bedded. Subparallel beds have rippled bases
3.0	0.91	Mudstone, red-brown, locally gray at base, sandy
3.0	0.91	Sandstone, fine-grained, thin-bedded. Subparallel beds have asymmetric rippled base
7.0	2.12	Sandstone, orange and tan, fine-grained, gypsiferous. Discontinuous parallel and ripple laminae near base. Top massive. Contact with underlying unit sharp and planar
2.0	0.61	Sandstone, olive-tan, very fine grained, ledge forming. Basal part firmly cemented with calcite
2.7	0.83	Sandstone, olive-tan, very fine to fine-grained; mainly covered by slope wash
4.3	1.31	Sandstone, white to light-tan, fine- to medium-grained, gypsiferous, indistinct parallel and ripple laminations. Crisscrossed by numerous healed fractures filled with sandstone
3.0	0.91	Sandstone, white to light-tan, medium-to fine-grained, indistinct ripple laminations. Grades into diamictite into lower part, with clasts of limestone and sandstone
2.0	0.61	Limestone, gray, dense, crystalline, thin-bedded. Basal beds platy
1.5	0.45	Limestone, gray, massive, pseudomicrobreccia. Very hard with irregular weathered surface
2.5+	0.76+	Gypsum, white, and gray limestone, mixed. Large gypsum nodules push aside limestone laminae

[1] *Rhizocorallium* at top

Figure 4. Measured section of the upper member of the Wanakah Formation near Ghost Ranch, N. Mex. (fig. 1, loc. 2). T, location of *Thalassinoides*; R, location of *Rhizocorallium*.

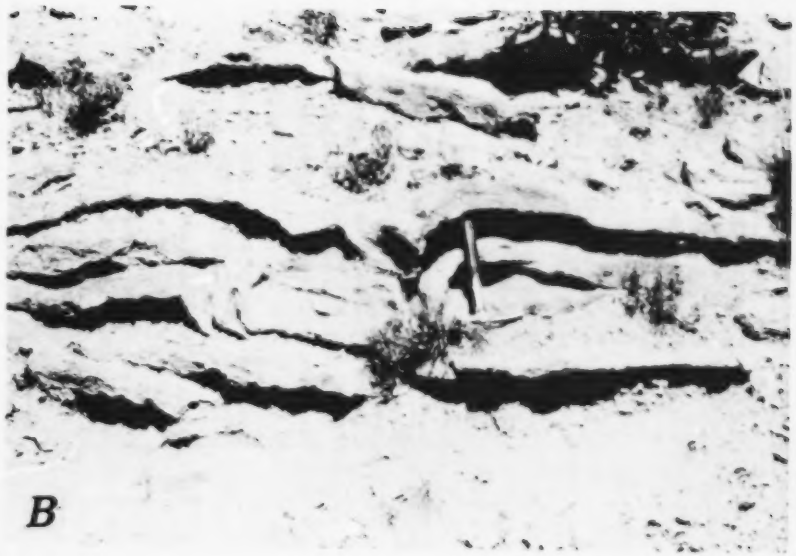
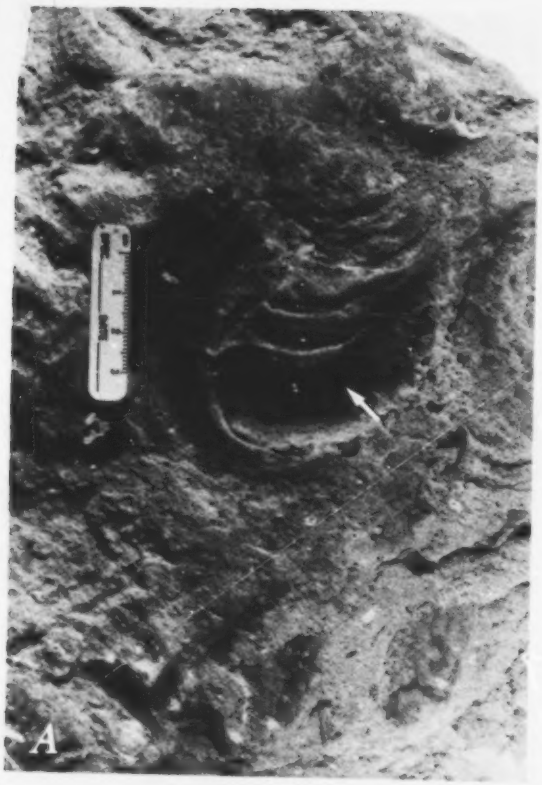


Figure 5 (above and facing page). Sedimentary features in the upper member of the Wanakah Formation. *A*, Basal diamictite containing randomly oriented clasts of sandstone and limestone. Hammer is at the undulatory contact with the underlying Todilto Limestone Member. *B*, Soft-sediment deformation in sandstone beds from the middle part of the upper member. Hammer shown for scale. *C*, Soft-sediment deformation, loading, and incipient formation of ball-and-pillow structures from the middle part of the upper member. Hammer shown for scale. *D*, Interference ripples from the upper part of the upper member. Pen shown for scale.

C

D



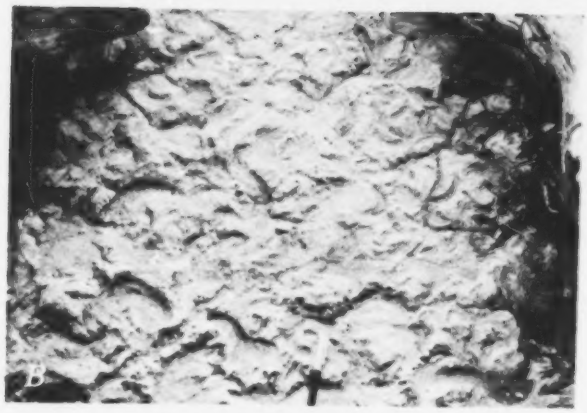


Figure 6 (above and facing page). Trace fossils from the upper member of the Wanakah Formation. Scale in centimeters except where object is used for scale. *A*, *Rhizocorallium*; center burrow shows well-developed spreite (arrow). *B*, Highly burrowed sandstone with numerous *Rhizocorallium* that crosscut one another. *C*, Boxwork *Thalassinoides*; note slightly nodose exterior of burrow. *D*, Part of *Thalassinoides* showing longitudinal striations and slightly nodose exterior. *E*, *Arenicolites*; note pairing of tubes and sparse distribution. *F*, *Arenicolites* occurring between as well as on oscillation ripples.

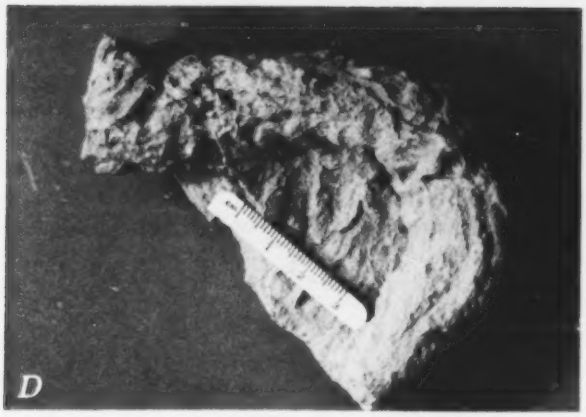
TRACE FOSSILS

Three morphologic types of trace fossils have been found in sandstone beds in the upper part of the Wanakah Formation. Figure 1 shows the localities at which the ichnofossils have been observed.

Rhizocorallium sp.

In the Chama basin, horizontal spreite-filled U-shaped burrows (fig. 5*A*) are the most common trace fossil in the upper member of the Wanakah Formation. The spreite consist of well-defined subparallel ridges and grooves cut into the sandstone (see, for example, fig. 6*A*). The U-shaped burrows have an outer tube width that ranges from 1.5 to 2 cm in diameter and an overall width and length that ranges from 4 to 8 cm. A few burrows are somewhat longer than wide; many, however, are wider than they are long. This difference in ratio of length to width may be a function of the degree of preservation. The burrows are wider at the openings between the tubes. Protrusive spreite between the external tubes are gently concave toward the opening between the tubes. In many beds, the external tube is poorly preserved or is not in the plane of the exposure and the ridge-and-groove pattern of the spreite is well displayed. Where the burrows are abundant, they crosscut one another (fig. 6*B*) and only portions of the burrows are preserved. The burrows are preserved in convex epirelief. The spreite-filled U-shaped burrows are similar to *Rhizocorallium jenense*; they differ from *Rhizocorallium jenense* redefined by Fürsich (1974) in that they are parallel with, rather than inclined to bedding and lack retrusive spreite.

Rhizocorallium is considered (Farrow, 1966; Fürsich, 1974) to represent a feeding structure as well as a temporary dwelling structure of a deposit feeder, probably some type of crustacean (Kennedy, 1975). The



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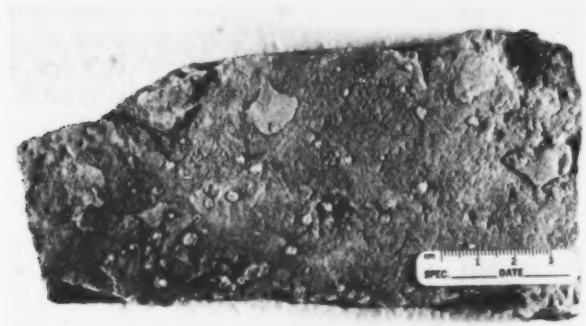

E

spreite, which form the arcs between the tubes, represent remnants of an earlier-formed base of the U (Osgood, 1975). The spreite are formed as the organism excavates the sediment in search of food. Farrow (1966) and Fürsich (1974) have also suggested that short traces may be made by a suspension feeder and longer traces by a deposit feeder. Thus, the fossil traces could have been made by more than one organism or by the same organism in response to changes in the physical energy conditions in the environment.

In the Chama basin, *Rhizocorallium* sp. has been found at a number of locations in the southern part of the basin (fig. 1). At some locations, more than one *Rhizocorallium*-bearing sandstone bed is present (fig. 4). Figure 4 shows a typical position of the *Rhizocorallium*-bearing beds in the upper part of the Wanakah. *Rhizocorallium*-bearing beds are found 10–15 ft (3–5 m) below the top of the formation. The burrows occur on the upper surface of flat-bedded, ripple-laminated, well-sorted, fine-grained sandstone. Ripple laminations are commonly preserved below the burrowed surface. The base of the sandstone is usually marked by well-developed oscillation or asymmetric ripples, and the sandstone is commonly overlain by mudstone or shale (fig. 3).

Thalassinoides sp.

Specimens of *Thalassinoides* from the Wanakah Formation have characteristics similar to *Thalassinoides paradoxica* Woodward 1830. (See Kennedy, 1967, for descriptions.) They also bear a strong physical resemblance to *Steinichnus carlsbergi* (Bromley and Asgaard, 1980), except that they have longitudinal rather than transverse striations, are more curved at branching points, and lack vuggy burrow filling. Because the specimens found represent only a small part of the larger burrow system, no formal species assignment is made at this time.

The cylindrical burrows are straight to curved and may overlap vertically to form a boxworklike structure (fig. 6*C*). Individual burrows are from 6 to 20 mm in diameter; vertical stacking of the burrows is 2 cm high. Bifurcation of the burrows is generally Y-shaped, and there is a pronounced curve where branches join; the angle of branching ranges from 90° to 120°. The exterior surface of the burrows is longitudinally striated to slightly nodose (figs. 6*C*, *D*). Transverse sections of the burrows show a uniform grain-size filling of material similar to that of the host rock. No distal terminations have been found. The burrows are preserved in convex hyporelief.

Thalassinoides is characteristically a horizontal, branching burrow having a smooth, striated, or slightly nodose exterior (Chamberlain, 1978). *Thalassinoides* sp. in the Wanakah exhibits similar branching habit, exterior ornamentation, and size range as reported for *Thalassinoides* from other geologic formations (Bromley, 1967; Kennedy, 1975; Chamberlain and Frey, 1978). *Thalassinoides* sp. was made by some type of arthropod or crustacean, an interpretation consistent with that proposed by Kennedy (1975) and Bromley (1967) for other horizontal *Thalassinoides*.

Thalassinoides sp. was found at one locality (figs. 1, 4). At locality 2 (fig. 4), the burrows occur about 9 ft (3 m) below the top of the formation on the underside of a greenish-gray, medium- to fine-grained sandstone. This

sandstone bed can be traced laterally for several hundred feet, and *Thalassinoides* sp. is locally present on the underside of this bed throughout this extent.

Arenicolites curvatus Goldring, 1962

Curved to slightly vertical U-shaped tubes ranging from 1 to 4 mm in diameter (figs. 6*E*, *F*) are identified as *Arenicolites curvatus* Goldring. Tubes are short, as long as 8 mm; some tubes may have extended into the underlying mudstone. The burrows occur as raised protuberances, approximately 1–2 mm, on the lower (convex hyporelief) and especially upper (convex epirelief) surfaces of sandstone beds. The tubes are filled with the same sediments that comprise the enclosing rocks. Filled burrows are somewhat lighter in color than the surrounding rock. No well-defined burrow wall is present. In several sections cut through one sample, the burrows were indistinct but appeared to have pronounced curvature. This curvature may be a result of the short tube length or of preservation of only the lower part of the U. The burrows are present in sparse to moderate numbers. Some of the burrows occur as pairs of equal-diameter tubes 1–8 mm apart. This pairing of tubes is characteristic of U- or J-shaped burrows (Osgood, 1970; Chamberlain, 1978).

Arenicolites, *Diplocraterion*, and *Skolithos* occur perpendicular or oblique to bedding and exhibit tube pairing or the appearance of tube pairing in sections cut normal to the tubes (parallel with bedding), so that accurate identification of the trace fossil must be made from sections cut parallel with the tubes. *Arenicolites* is defined as a vertical to curved, U-shaped burrow that lacks spreite (Goldring, 1962; Chamberlain, 1978). *Diplocraterion* is characterized by a vertical, spreite-filled, U-shaped burrow that in plan section appears as paired tubes with a connecting structure having a dumbbell shape (Osgood, 1970; Chamberlain, 1978). *Skolithos* occurs as straight to inclined single burrows (Osgood, 1970; Chamberlain, 1978); where closely spaced, the burrows can be mistaken for paired tubes. The U-shaped burrows in the upper member of the Wanakah are considered to be those of *Arenicolites*, based on the U-shape of the burrow and the absence of spreite.

Arenicolites has been found at three localities (fig. 1, locs. 3, 8, 15) in the upper part of the formation above *Rhizocorallium* beds. At locality 8, they occur in fine-grained, reddish-brown sandstone, about 2 ft (0.6 m) from the top of the formation. At locality 3, they occur in light-grayish-white, thin-bedded, and commonly rippled sandstone (fig. 6*F*), about 3 ft (1 m) from the top of the formation. At localities 3 and 15, numerous burrows cover the surface of the sandstone and occur both between and on oscillation ripples.

NONMARINE MOLLUSK

One type of mollusk has been found in the upper member of the Wanakah in the Chama basin. It has been identified as the nonmarine mollusk *Vetulonaia* sp. by Steve C. Good (oral commun., 1986). The species has not been determined. A thorough study of this mollusk is currently being conducted by Good as part of a doctoral dissertation at the University of Colorado.

Vetulonaia sp.

Two whole specimens and numerous fragments of the nonmarine mollusk *Vetulonaia* were recovered from green, muddy, micritic limestone from an outcrop north of Ghost Ranch (fig. 1, loc. 15). S.C. Good tentatively identified the mollusk as a type of *Vetulonaia* based on the presence of a deep groove along one side where the shells join (fig. 7). The mollusks are 25 mm and 8.8 cm in diameter and occur 3–4 ft (1–1.2 m) below the *Rhizocorallium*- bearing sandstone at that locality. The original shell material has been replaced by pink chert. Although the mollusk-bearing bed is laterally extensive, the mollusks occur only locally. Where the mollusks are absent, pieces of amorphous pink chert are present.

PALEOENVIRONMENTAL INTERPRETATION

The suite of trace fossils and the mollusk are confined to the upper 15–20 ft (5–6 m) of the upper member of the Wanakah; no trace fossils or mollusks were found below this depth. The suite of trace fossils, particularly *Rhizocorallium* sp., is normally associated with marine depositional environments and would suggest that Wanakah sediments in the Chama basin were deposited in a body of water associated with marine rather than continental depositional conditions. The presence of the nonmarine mollusk in strata underlying strata containing the trace fossils indicates, however, a lacustrine depositional setting for the upper part of the upper member of the Wanakah Formation.

Rhizocorallium commonly is reported from strata for which marine environments, including lagoonal, backshore, and upper offshore (nearshore) have been ascribed (Farrow, 1966; Frey, 1975; Chamberlain, 1978; Seilacher, 1978). In the Chama basin, *Rhizocorallium* sp. is horizontal and occurs parallel with bedding. The density of the burrows ranges from sparse to abundant, and orientation of the long dimension of the tubes is random. In a study of *Rhizocorallium* in the Jurassic Scarborough Limestone of England, Farrow (1966) showed two bathymetric zonations, based on the

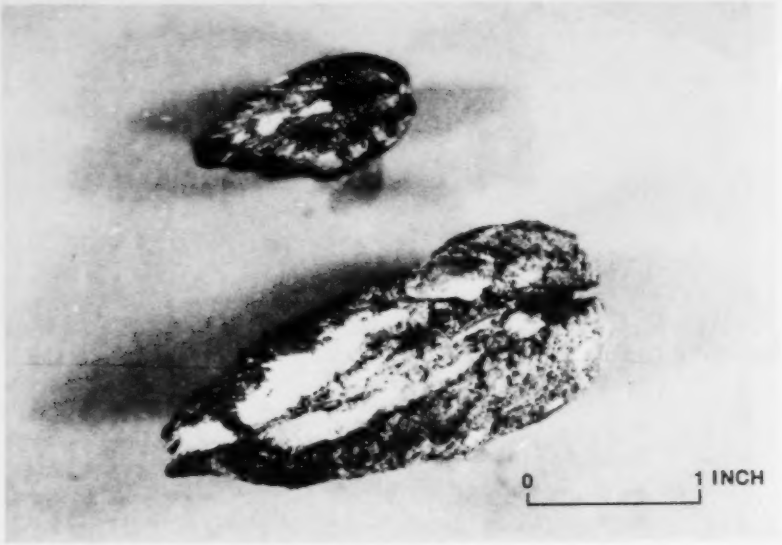

Figure 7. Nonmarine mollusk *Vetulonaia* from the upper member of the Wanakah Formation. Note pronounced groove on one side, where the shells join.

orientation of these burrows. Parallel-oriented *Rhizocorallium* were interpreted to occur in the intertidal zone. The burrows are oriented perpendicular to the shoreline; this orientation is believed to be a response to tidal currents. Randomly oriented *Rhizocorallium* were believed to occur in water, below the tidal zone, but above wave base. In addition, the randomly oriented burrows occur in rocks that contained oscillation ripples.

Rhizocorallium sp. of the Chama basin exhibit characteristics similar to those of Farrow's randomly oriented type. The horizontal, random orientation and the presence of oscillation or asymmetric ripples in beds containing the burrows suggest that *Rhizocorallium* sp.-bearing strata of the Chama basin accumulated in nearshore zones above effective wave base. The horizontal to slightly oblique orientation of the burrows indicates quiet water and low rates of sedimentation. *Rhizocorallium* sp. in the Chama basin bears some resemblance to *Rhizocorallium communis* reported from the freshwater Triassic Fleming Fjord Formation in Greenland (Bromley and Asgaard, 1980). In the Fleming Fjord Formation, *Rhizocorallium communis* occurs in fine-grained, flat-bedded, and wave-rippled sandstone in the lower 30 ft (9 m) of the formation. Conchostracons occur in the same stratigraphic interval. On the basis of the presence of conchostracons and of mudcracks in beds above and below the sandstone containing the *Rhizocorallium*, Bromley and Asgaard suggested a freshwater lacustrine origin for the *Rhizocorallium communis*.

Thalassinoides has been reported from strata deposited in a variety of marine environments, including lagoonal, intertidal, and shoreface to lower offshore zones (Frey, 1975; Kennedy, 1975; Chamberlain, 1978; Seilacher, 1978). Although *Thalassinoides* is generally associated with marine depositional environments, Bromley and Asgaard (1980) have reported a trace fossil, *Steinichnus carlsbergi*, similar to *Thalassinoides*, from rocks characteristic of wet subaerial environments near stream edges. Although there are significant differences in ornamentation and type of burrow filling between *Thalassinoides*, *Thalassinoides* sp., and *Steinichnus carlsbergi*, the morphology of the burrows is similar and suggests formation in subaqueous or subaerial depositional environments having slow rates of sedimentation. In the Chama basin, *Thalassinoides* sp. has been found at only one locality. The burrows occur in a bed a few feet above beds containing the *Rhizocorallium* sp. (fig. 4). A limestone bed overlies the sandstone bed containing the *Thalassinoides* sp. The horizontal orientation of *Thalassinoides* sp., the presence of overlying limestone and thin-rippled sandstone (fig. 4), and the absence of mudcracks in beds below the *Thalassinoides* sp.-bearing sandstone all suggest deposition of the *Thalassinoides* sp.-bearing sandstone in quiet-water, nearshore environments with low sedimentation rates.

Arenicolites is known to occur in marine intertidal, backshore, foreshore, and upper (nearshore) to lower offshore zones that are characterized by high-energy conditions (Frey and Howard, 1970; Crimes, 1975; Chamberlain, 1978). It has also been reported from lacustrine environments (Bromley and Asgaard, 1980). Organisms creating the burrows are primarily suspension feeders; they create vertical burrows in response to fluctuations in the rate of sedimentation that occur in the

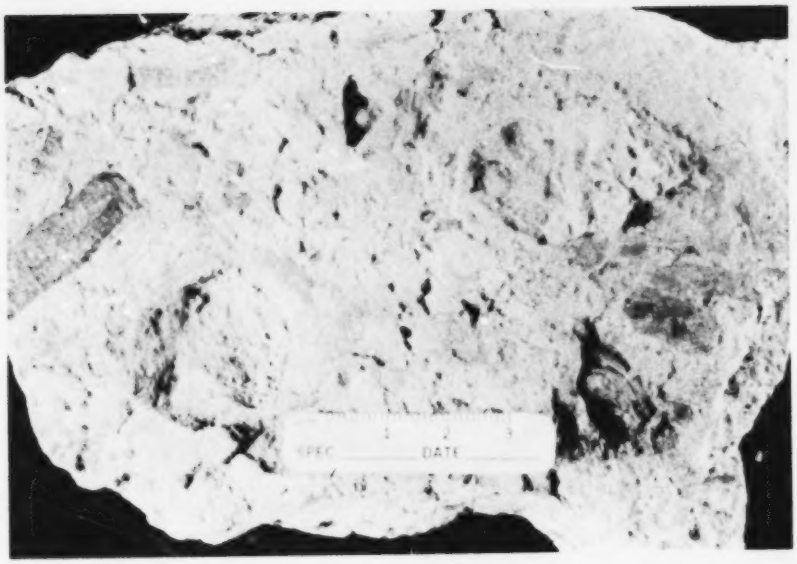

Figure 8. Carbonaceous sandstone collected from near the top of the upper member of the Wanakah Formation (fig. 1, loc. 6).

higher energy depositional environments. In the Chama basin, *Arenicolites curvatus* has been found at three localities (fig. 1, locs. 3, 8, 15). The burrows occur in ripple-bedded sandstones a few feet below the top of the formation and several feet above the *Rhizocorallium* sp.-bearing beds. The presence of oscillation ripples in the sandstone containing the *Arenicolites curvatus* indicates a depositional environment within wave base. The vertical burrows indicate conditions of rapid sedimentation. The conditions of rapid sedimentation coupled with wave action producing oscillation ripples are characteristic of nearshore lacustrine environments associated with late-stage infilling of the lake by fluvially transported sediments.

Rocks overlying the *Arenicolites*-bearing sandstone are mainly rippled sandstone locally interbedded with thin mudstone. At or near the top of the Wanakah at several locations, a thin limestone bed commonly contains thin-shelled ostracodes and at two locations also contains charaphytes. The limestone beds are laterally discontinuous and are interpreted to have formed in coastal ponds. At locality 6 (fig. 1), a thin, very carbonaceous sandstone (fig. 8) is found a few inches above one of these limestone beds; it is overlain by and laterally pinches out into a thin bed of light- to dark-gray carbonaceous mudstone. This sandstone-mudstone sequence is indicative of deposition in a marginal-lacustrine marshy environment.

The nonmarine mollusk *Vetulonaia* is found in both fluvial and lacustrine environments of deposition (S.C. Good, oral commun., 1986). A lacustrine origin is preferred based on the occurrence of the mollusks in muddy, micritic limestone rather than sandstone and on their occurrence stratigraphically below beds containing the trace fossils of obvious subaqueous origin. No mudcracks or other evidence of subaerial exposure occur in beds separating the mollusk- and trace fossil-bearing

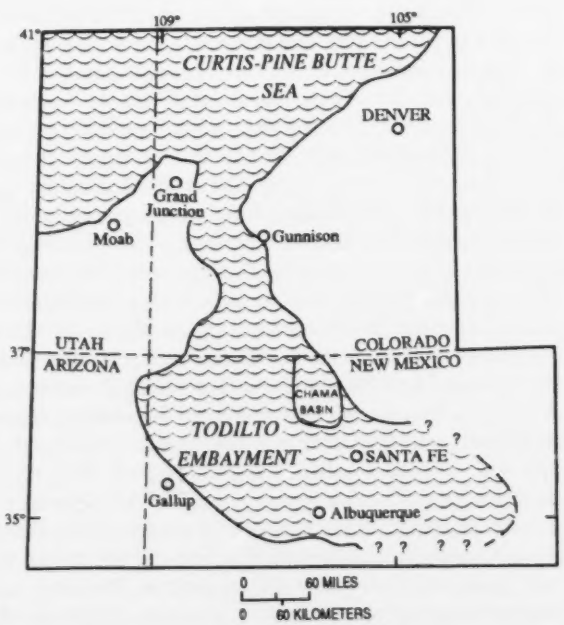

Figure 9. Areal extent of the Curtis-Pine Butte sea and Todilto embayment (wavy patterned area) during middle Callovian time in area of Utah, Colorado, New Mexico, and Arizona.

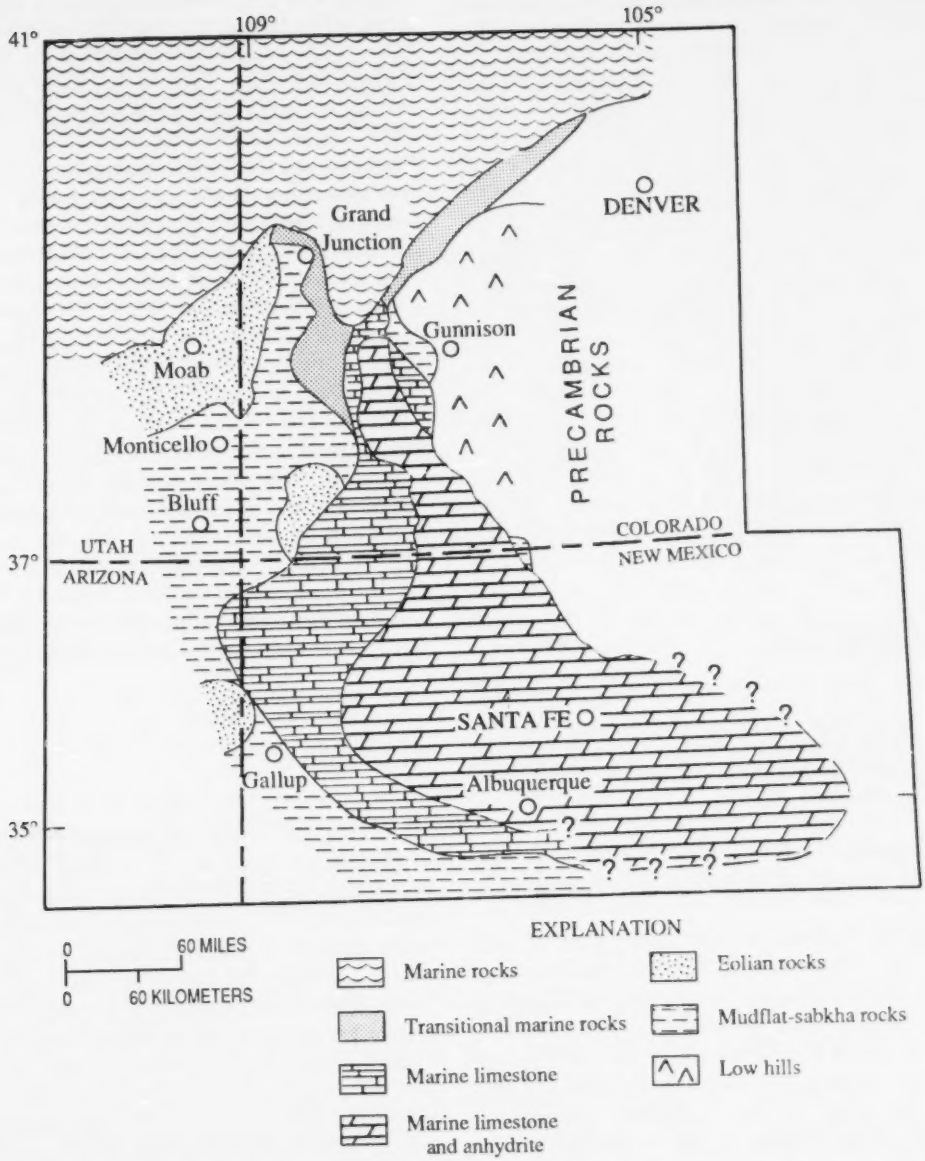

Figure 10. Paleogeography at the time of deposition of the Todilto Limestone Member of the Wanakah Formation in area of Utah, Colorado, New Mexico, and Arizona. Query indicates location of boundary uncertain.

beds. The muddy, micritic limestone is commonly about 2 ft (0.7 m) thick and was deposited in a nearshore, quiet-water carbonate-flats environment that received only minor amounts of clastic sediments. The limestone is thoroughly bioturbated. Fragmentation of the shells may have been caused by storms that reworked the upper sediment layer.

At several localities, basal sandstone beds of the overlying Morrison are slabby, rippled, and burrowed and contain soft-sediment deformation structures characteristic of subaqueous deposition. The basal sandstone beds occur in laterally discontinuous lenses encased in mudstone or in scours cut into the underlying Wanakah. The thickness and lateral continuity of the lower Morrison sandstone units increases upward. All these relationships suggest that deposition was continuous from the Wanakah to the lower part of the Morrison and that no significant time break occurs at the formation contact. In the Chama basin, the lower part of the Morrison was apparently deposited as the distal

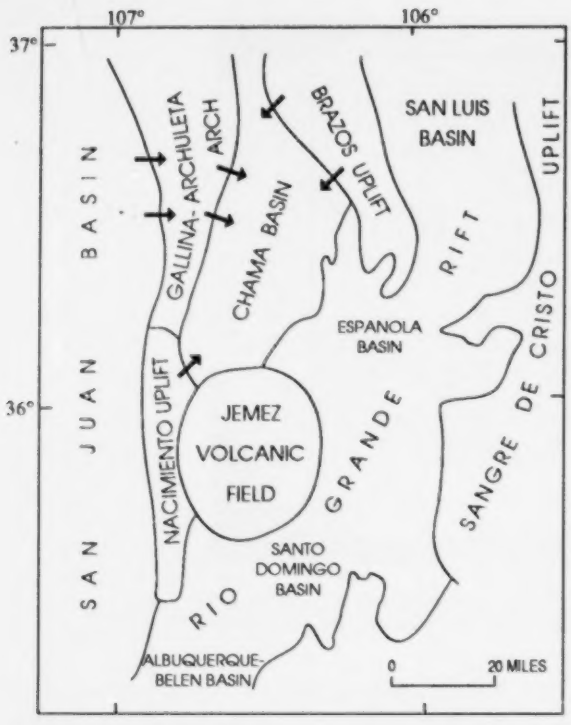

Figure 11. Active tectonic features at the close of Todilto deposition, Chama basin, New Mexico. Arrows indicate source of sediment and direction of sediment transport. Modified from Woodward (1974).

part of a dominantly fluvial system that prograded over the regressive, nearshore lacustrine sediments of the Wanakah.

A lacustrine origin for the upper part of the Wanakah is consistent with a new interpretation of regional stratigraphic relations for this interval (Ridgley, 1987). During middle Callovian time, a marine invasion is known to have extended from the north into central Colorado (Imlay, 1980). The Curtis Formation and the Pine Butte Member of the Sundance Formation, considered by Imlay (1980) to be correlative, were deposited at this time in a variety of marine environments. Recent studies by Ridgley (1984) of the Todilto Limestone and Pony Express Limestone Members of the Wanakah Formation, considered to be correlative to the Curtis and Pine Butte, indicate that the marine invasion during middle Callovian time actually extended into north-central New Mexico. The Todilto and Pony Express formed in a restricted marine embayment that joined with the Curtis-Pine Butte sea to the north Ridgley, 1984), just west of Gunnison, Colo., and not in a large, saline lake as proposed by Anderson and Kirkland (1960). The marine interpretation for the origin of the Todilto and Pony Express is based in part on stable carbon and sulfur isotope data (Ridgley and Goldhaber, 1983). Figure 9 shows the areal extent of the Curtis-Pine Butte sea and the Todilto embayment. Figure 10 shows a reconstruction of the paleogeography during Todilto time and is based on all available surface and subsurface data pertaining to the rock units of this time period in the area shown. All the marine limestone and anhydrite shown in figure 10 are the Todilto and Pony Express Limestone Members. At the close of Todilto deposition, uplift in the Brazos uplift, Nacimiento uplift, and along the Gallina-Archuleta arch served to isolate marine waters to the Chama basin, and, subsequently, a large lake formed in the basin (fig. 11) (Ridgley, 1987).

The extent of lacustrine conditions during late Wanakah time is unknown. On the basis of the trace fossil and mollusk evidence, the lake can be extended with certainty as far south as the southern part of the Chama basin, and it probably extended northward into southern Colorado. Additional field studies are needed to document the northward extension of the lake.

SUMMARY

The trace fossil assemblage (*Rhizocorallium* sp., *Thalassinoides* sp., and *Arenicolites curvatus*) and the nonmarine mollusk (*Vetulonaia*) in the upper part of the upper member of the Wanakah Formation of the Chama basin indicate that during middle and upper Callovian time a large lake covered the southern part of the Chama basin. The assemblage is characteristic of shallow nearshore lacustrine environments. Near the top of the Wanakah, discontinuous ostracode- and charaphyte-bearing limestone and carbonaceous sandstone and mudstone, which occur stratigraphically higher than the trace fossil-bearing strata, represent deposition in coastal ponds and marshes. The vertical succession of mollusks, trace fossils, and ostracodes-charaphytes corresponds to changes in thickness and sedimentary structures of sandstone, mudstone, and limestone beds, and it reflects the gradual infilling of the lake. The upper part of the upper member of the Wanakah Formation and the lower part of the Morrison Formation in the Chama basin represent a continuum of depositional environments extending from shallow lacustrine to fluvial.

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Chapter D

Stratigraphy, Facies, and Paleotectonic History of Mississippian Rocks in the San Juan Basin of Northwestern New Mexico and Adjacent Areas

By AUGUSTUS K. ARMSTRONG and LEE D. HOLCOMB

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

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PLATE

[Plate is in pocket]

1. Surface outcrop and subsurface sections showing Mississippian rocks, Utah, Colorado, and New Mexico.

FIGURES

1–2. Maps showing:
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CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C = (temp °F–32)/1.8

Stratigraphy, Facies, and Paleotectonic History of Mississippian Rocks in the San Juan Basin of Northwestern New Mexico and Adjacent Areas

By Augustus K. Armstrong[1] *and* Lee D. Holcomb[2]

Abstract

Lowermost Mississippian rocks in the San Juan basin of northwestern New Mexico are Kinderhookian(?) and earliest Osagean in age and are restricted to the western margins of the basin. They overlie rocks of Late Devonian age and were laid down as carbonate sediments during a regional transgression in northern New Mexico. The Osagean marine transgression moved east and south from the Four Corners region and north from south-central New Mexico, flooding a terrane of Precambrian igneous and metamorphic rocks. The Precambrian surface on which the transgression occurred was irregular, and islands above the late Osagean sea included the Zuni-Defiance highlands, the Uncompahgre highlands, and the Pedernal highlands. The Osagean rocks that formed adjacent to the highlands include supratidal and intertidal lime mudstone, anhydrite, gypsum, dolomite, quartz sandstone, and shale. In more open marine environments, calcareous sand shoals were composed of pellets, bioclasts of crinoids, brachiopods and bryozoans, and ooids and oolites. The end of Osagean time was marked by regional marine regression and uplift and erosion of the carbonate platform.

A regional marine transgression during Meramecian time is documented in the upper part of the Redwall Limestone in the subsurface of the Black Mesa basin in northeastern Arizona, in the upper part of the Leadville Limestone in the subsurface of the western part of the San Juan basin in New Mexico and equivalent rocks in southeastern Utah, and in outcrops of the Tererro Formation of the Arroyo Penasco Group in the Nacimiento and San Pedro Mountains on the eastern side of the San Juan basin in New Mexico. These marine bioclastic carbonate rocks are composed of dolomite, lime mudstone, oolites, crinoids, foraminifera, algae, brachiopods, and pellets

In Late Mississippian time, the region was differentially uplifted and large areas of Mississippian rocks were removed. The remaining carbonate rocks were subjected to solution and a thick regolith developed. On the east flank of the San Juan basin, in the San Pedro and Nacimiento Mountains, Mississippian carbonate rocks of the Arroyo Penasco Group are unconformably overlain by continental red beds of the uppermost Mississippian (Chesterian) Log Springs Formation. Reworking of this continental regolith by the transgressive Pennsylvanian sea to form the Molas Formation is documented in the San Juan Mountains and in the subsurface. Throughout the region, Mississippian sedimentary rocks are truncated by Pennsylvanian sedimentary rocks.

INTRODUCTION

The present-day San Juan basin is a strongly asymmetrical, rhombic-shaped depression, and thick accumulations of Cretaceous and Tertiary rocks have buried many Paleozoic structures. Paleozoic structures in the basin include northwest-trending faults of the San Luis uplift, the Four Corners lineament, the Tocito horst, and the Zuni uplift. The Four Corners platform, bounded by the House Creek fault and the Hogback monocline, is a prominent northeast-trending feature that separates the Paradox basin to the north from the San Juan basin to the south. The basin is bounded on its west and east sides by the north-trending Defiance and Nacimiento uplifts, respectively (Stevenson, 1983a).

Reconstruction of the biostratigraphy and paleogeography of the Mississippian System in the area of the San Juan basin is difficult because of the poor subsurface data base (fig. 1). Over the years, many cores and cuttings

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have been lost or scattered and are not available for study. Outcrop sections adjacent to the San Juan basin are in widely separated mountain ranges (fig. 2) and consist of very thin, condensed carbonate sections that contain numerous hiatuses and have been subjected to postdepositional solution and brecciation (fig. 3).

Lithologic correlations for Mississippian carbonate rocks are not reliable unless a good biostratigraphic framework is established, and paleogeographic and paleotectonic reconstructions cannot be made without accurate correlations. For outcrop sections in the region, we used the microfossil zonation established by B.L.

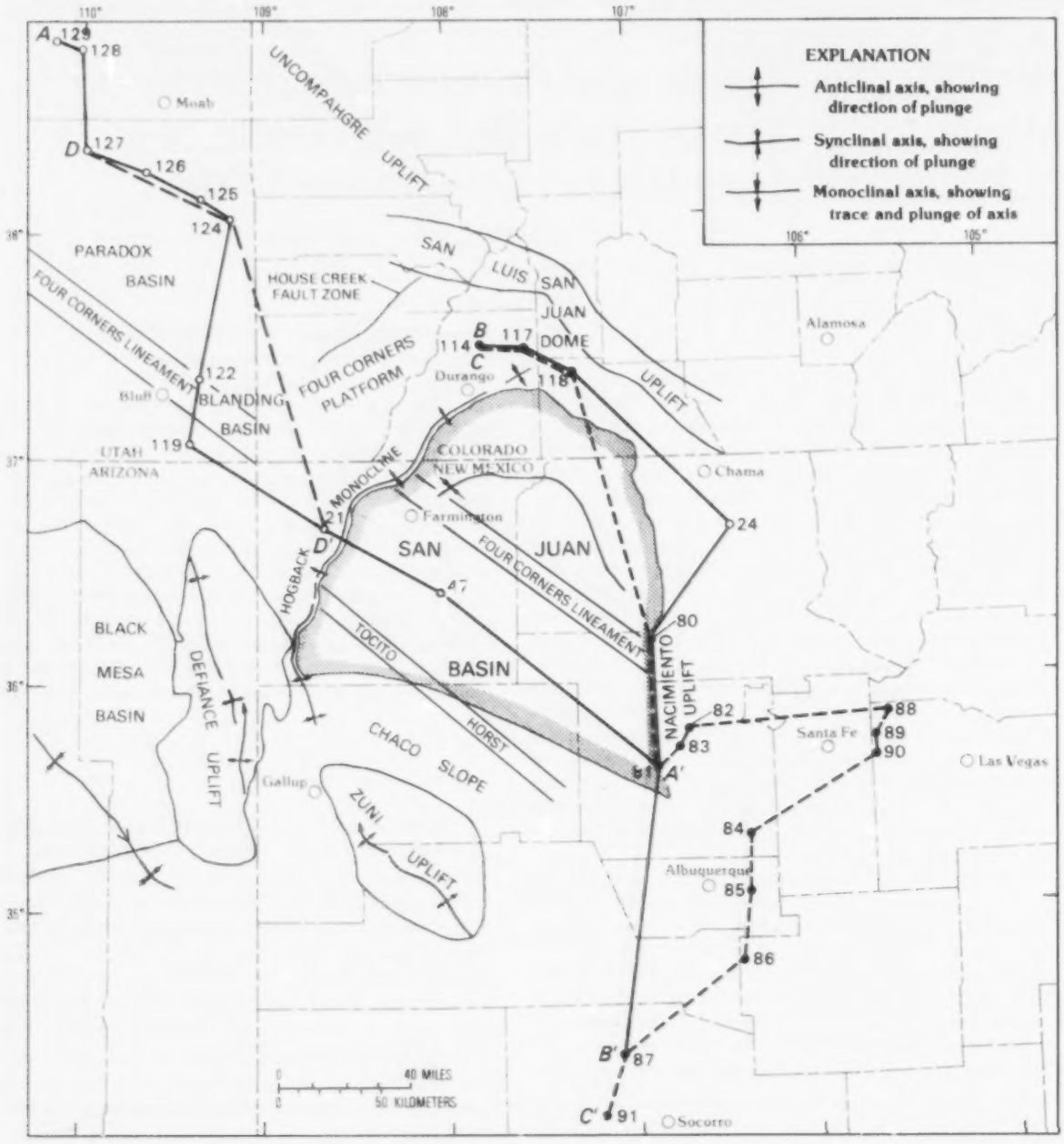


Figure 1. Structural features in the San Juan basin of northwestern New Mexico and adjacent areas. Names of features from Kelley and Clinton (1960) and Stevenson (1983a). Lines of sections *A–A'*, *B–B'*, *C–C'*, and *D–D'* (plate 1) and locations of surface (closed circles) and subsurface (open circles) measured sections (appendixes 1, 2) also shown.

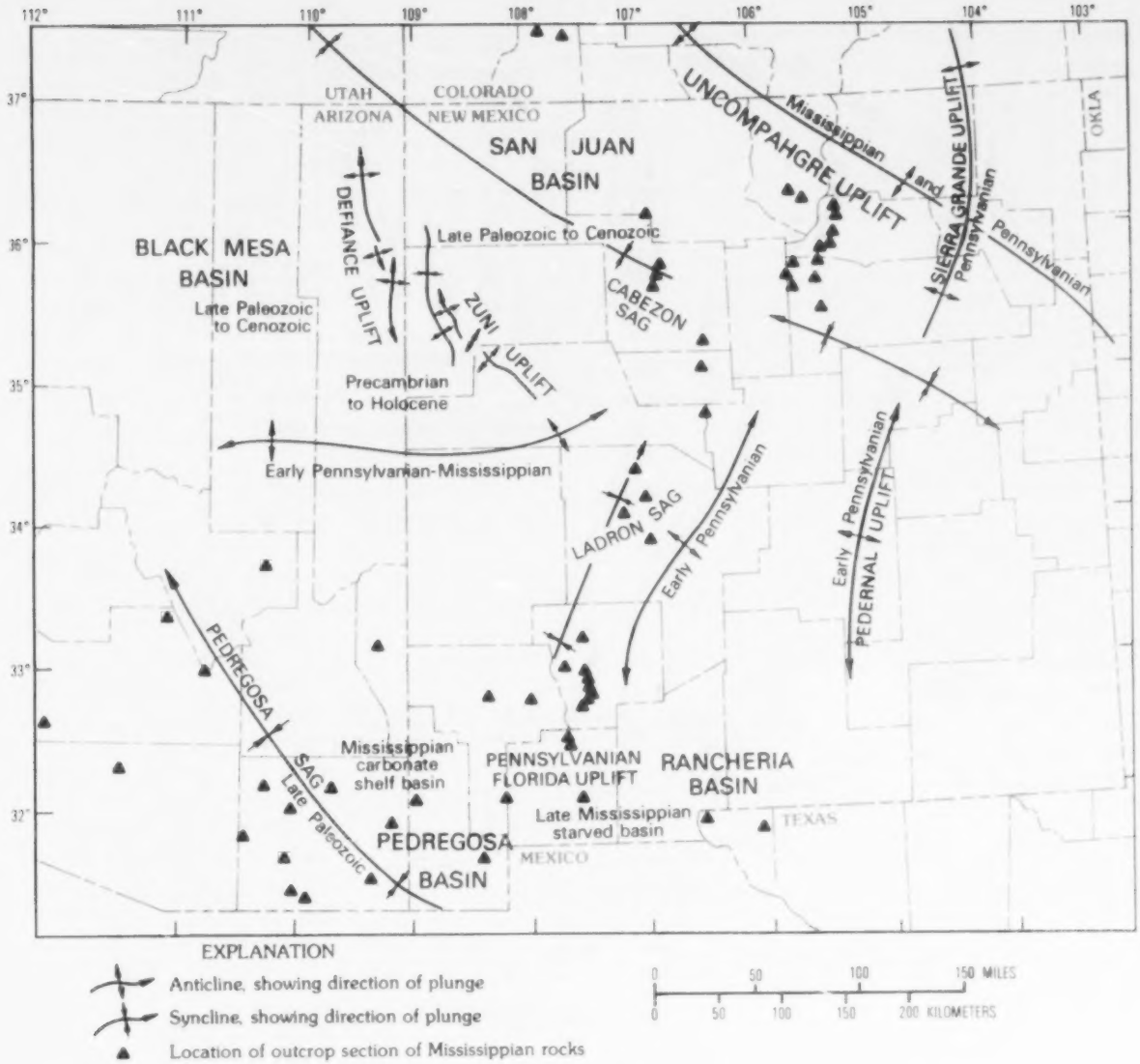


Figure 2. Paleotectonic map for Mississippian rocks of New Mexico and eastern Arizona.

Mamet (Sando and others, 1969), Mamet and Skipp (1970), Armstrong and Mamet (1974, 1976, 1977a,b) and Armstrong and others (1979). For the subsurface, we used unpublished Shell Oil Company microfossil reports compiled by L.D. Holcomb (1960–1972). Holcomb's subsurface micropaleontologic studies and lithologic logs of wells were used to develop the subsurface isopach map, cross sections, and paleogeographic reconstructions (pl. 1). Studies of outcrops from adjacent mountain ranges by Armstrong (1958, 1967), Armstrong and Mamet (1974, 1977a,b), and Armstrong and others (1979) were used to determine both regional correlations and the sedimentological and tectonic history of areas adjacent to the San Juan basin. The carbonate rock classification scheme of Dunham (1962) was used in this study. The San Juan basin and adjacent area, as used in this report, includes parts of northwestern New Mexico and southwestern Colorado, and small areas in southeastern Utah and northeastern Arizona.

Acknowledgments.—We express our appreciation to Shell Oil Company and to Dana Kent Clark, Staff Paleontologist, and T.D. Cook, Manager, Stratigraphic Services, for making available L.D. Holcomb's paleontological and stratigraphic reports on the subsurface of the San Juan basin. Dr. Frank K. Kottlowski, Director, New Mexico Bureau of Mines and Mineral Resources, has over the decades given financial and intellectual support to our study of the Mississippian System of

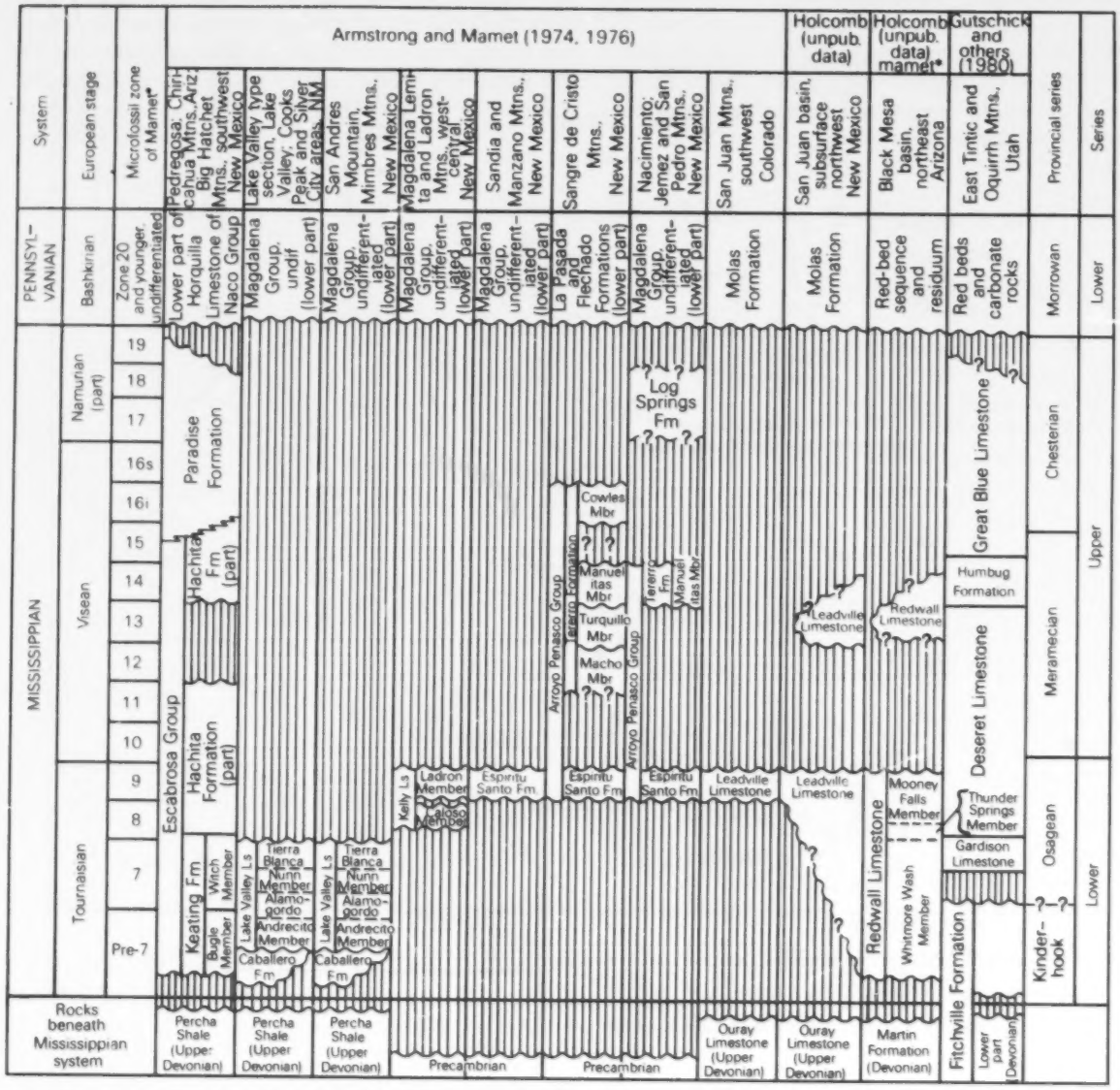


Figure 3. Regional correlation chart for the Mississippian System, San Juan basin of northwestern New Mexico and adjacent areas. Black Mesa basin stratigraphy is also from Mamet and Skipp (1970).

New Mexico. Jennie L. Ridgley and Steven M. Condon, U.S. Geological Survey, gave their time and effort in reviewing this manuscript.

REGIONAL STRATIGRAPHY AND CORRELATIONS

In the San Juan basin and adjacent areas, rocks of Mississippian age are mapped as the Leadville Limestone and equivalent rocks, the Redwall Limestone, the Arroyo Penasco Group, and the Log Springs Formation (fig. 3.) In the northern and western parts of the San Juan basin, Mississippian rocks unconformably overlie the Upper Devonian Ouray Limestone or Elbert Formation, which lies beneath the Ouray. On the east side of the San Juan basin and in the Nacimiento and San Pedro Mountains, Mississippian strata rest unconformably on Precambrian igneous and metamorphic rocks.

The Leadville Limestone typically is a complex sedimentary suite of cratonic carbonate rocks that are generally devoid of terrigenous clastic material. Pellet-echinoderm-ooid foraminifer packstone and wackestone and minor amounts of lime mudstone are the most

common rock types; no organic reefs or waulsortian mounds are known within the Leadville Limestone. Dolomite in the Leadville Limestone formed by replacement of lime mudstone and coarse-grained encrinite. Nodular light-gray to dark-brown-gray chert is also common.

McKee (1951) published isopach maps for the Devonian and Mississippian Systems of northwestern New Mexico. Parker and Roberts (1963) correlated the Leadville Limestone of the San Juan Mountains and the subsurface of the San Juan and Paradox basins with the Redwall Limestone of the Grand Canyon region of Arizona. They considered the lower part of the Leadville Limestone at Rockwood Quarry, Colo., to be equivalent to the Thunder Springs Member (McKee, 1963) of the Redwall Limestone and the upper part of the Leadville to be equivalent to the Mooney Falls Member. Their correlations are based on analysis of subsurface electric logs from eastern Arizona.

Studies of the lithology and paleontology of the Redwall Limestone by McKee and Gutschick (1969) and McKee (1972, 1979) indicate that the Mooney Falls Member represents the maximum preserved eastward trangression of the Redwall Limestone. A limestone unit recognized in the subsurface of the Black Mesa basin of Arizona is assigned to the Meramecian part of the Redwall Limestone (fig. 3). This unit may be part of, or equivalent to, part of the Mooney Falls Member to the west or the younger Horseshoe Mesa Member of the Redwall. Microfossil studies of surface sections of the Leadville Limestone of the San Juan Mountains by B.L. Mamet (Sando and others, 1969) show the Leadville Limestone to be equivalent to the middle part of the Mooney Falls Member of the Redwall Limestone. Numerous oil tests drilled in the Black Mesa basin of northern Arizona and the Paradox basin of Utah show continuous Mississippian carbonate beds in the subsurface from the west side of the Wasatch Mountains of north-central Utah and the east side of the Grand Canyon to the east edge of the San Juan basin (fig. 3, pl. 1).

Mississippian strata in the subsurface of the San Juan basin have been assigned to the Redwall Limestone in various studies, including many of the American Stratigraphic Company's stratigraphic logs, particularly those in the western part of the basin. Stevenson (1983b, fig. 2) assigned Mississippian rocks in the Four Corners region to the Leadville Limestone and those in the southeastern part of the San Juan basin to the Arroyo Penasco Group. It is generally agreed that Mississippian rocks in the Black Mesa basin are the Redwall Limestone, Mississippian rocks in the Paradox basin of southeastern Utah are the Leadville Limestone, and those to the west of the Paradox basin are the Redwall Limestone (Stevenson, 1983b).

Microfossil reports by L.D. Holcomb for Shell Oil Company were used in this study to indicate the age of the Redwall Limestone in the Black Mesa basin of Arizona and of the Leadville Limestone in the San Juan basin of New Mexico. These age determinations are based on Holcomb's studies of endothyrids in cuttings and cores of exploration wells. His endothyrid zonation is based on American studies (Zeller, 1950, 1957) and is not as refined as the subsequently produced European and Russian zonations. Mamet introduced these greatly refined zonations to North America (Sando and others, 1969) (fig. 3). Holcomb's subsurface zonation is not as detailed as Mamet's zonation for outcrops in the mountain ranges of southern Colorado and New Mexico. Holcomb recognized that the upper part of the Leadville Limestone in the subsurface is Meramecian in age. This age assignment was based on the recognition of a distinctive suite of foraminifera, characterized by *Eoendothyranopsis macra* (Zeller), in the upper part of the Leadville Limestone.

The Mississippian Arroyo Penasco Group crops out on the east flank of the San Juan basin in the San Pedro and the Nacimiento Mountains and comprises two formations, the Lower Mississippian (Osagean) Espiritu Santo Formation (Baltz and Reed, 1960) and the overlying Upper Mississippian (Meramecian and Chesterian) Tererro Formation. Its basal unit, the Del Padre Sandstone Member (Sutherland, 1963) of the Espiritu Santo Formation, is 1–20 ft (0.3–6.1 m) thick and is composed of quartz conglomerate, sandstone, siltstone, and thin shale. It interfingers with carbonate rocks of the Espiritu Santo Formation and rests unconformably on Precambrian igneous and metamorphic rocks (fig. 3, pl. 1).

Carbonate rocks of the Espiritu Santo Formation include dolomite and dedolomite; coarse-grained poikilotopic calcite commonly has corroded dolomite rhombs. Stromatolitic algal mats, spongiostronata mats, echinoderm wackestone, kamaenid birdseye-rich lime mudstone, and oncholitic-bothrolitic mats have been recognized in areas where the rock is not dolomitized.

The Espiritu Santo Formation is disconformably overlain by the Upper Mississippian Tererro Formation of the Arroyo Penasco Group. The *Eoendothyranopsis macra* (Zeller) fauna is typical of the upper part of this formation. The Tererro Formation is composed of thickly bedded, oolitic-bothrolitic grainstone and a silty, pelletal, fine-grained grainstone-packstone containing minor amounts of calcareous silt. The Tererro Formation is younger than the Leadville Limestone of the San Juan Mountains, and the absence of Meramecian beds in the San Juan Mountains is believed to be the

result of late Chesterian and Early Pennsylvanian erosion. Meramecian carbonate rocks are, however, in the subsurface of the Paradox basin of southeastern Utah, the Black Mesa basin of northwestern Arizona and the San Juan basin of northeastern New Mexico (pl. 1).

The Upper Mississippian Log Springs Formation (Armstrong, 1955) crops out on the east flank of the San Juan basin in the San Pedro, Nacimiento, and Jemez Mountains and is 1–80 ft (0.3–24 m) thick. Extensive solution of the underlying limestones of the Tererro Formation has resulted in brecciation and solution cavities filled with basal ferruginous shales of the Log Springs Formation. The Log Springs Formation was deposited in a continental-fluvial environment. The beds have well-developed cut-and-fill channel structures. The Log Springs Formation is a sequence of maroon to gray shale, sandstone, and conglomerate. The lower part of the formation contains beds of pisolitic hematite and ferruginous shale. The lower sandy conglomerates of the formation contain a few sporadically distributed, rounded pebbles of Mississippian chert; clasts in conglomerates higher in the formation are angular to subrounded pebbles to boulders of Precambrian granite and schist and Mississippian chert and carbonate rocks. The Log Springs Formation rests with angular unconformity on the karst surface of the Arroyo Penasco Group and in turn is overlain with angular unconformity by fossiliferous Morrowan limestones. Because the Log Springs Formation is younger than Mamet's zone 16i and is overlain by Morrowan fossiliferous limestones of zone 20 (fig. 3), it must be Chesterian age equivalent (Armstrong and Mamet, 1974, 1976).

The Lower Pennsylvanian Molas Formation typically is a clastic red-bed sequence of silty variegated shale containing chert or limestone nodules, red to brown siltstone, and limestone. The lower part of the Molas Formation is believed to be a residual soil that covers a karst surface on the Leadville Limestone (Szabo and Wengerd, 1975). Merrill and Winar (1958) stated "The lower Coalbank Hill Member of the Molas Formation can be defined only by its stratigraphic position, post-Leadville, pre-Middle Molas. The Mississippian-Pennsylvanian boundary is probably contained within it or the overlying member." The Molas Formation is a time-transgressive unit. Fusulinids were identified as late Chesterian to early Desmoinesian in age by M.L. Thompson for Merrill and Winar (1958), who stated that fossils of Leadville age were found in residual chert pebbles in the Molas, and fossils of Early and Middle Pennsylvanian age were found in the upper 10 ft of the Molas. We believe that the Molas is, in part, an old regolith formed in late Chesterian time and reworked by Morrowan waters.

MISSISSIPPIAN CARBONATE FACIES AND DIAGENESIS

Conceptional facies models for the Leadville Limestone and the Arroyo Penasco Group are shown in figures 4 and 5 and were derived in part from the carbonate-facies models of Wilson (1975), James (1984), and Harris and others (1985). The Leadville Limestone, as indicated by outcrop studies of Armstrong and Mamet (1976), is a series of incomplete, upward-shoaling carbonate cycles (figs. 4, 5). Studies of the Leadville Limestone and the Espiritu Santo Formation by Armstrong (1967) and Ulmer and Laury (1984) indicate lagoonal to supratidal environments of deposition for parts of these formations, similar to those in the present-day Persian Gulf (Evans and others, 1973; Purser and Evans, 1973; Shinn, 1973; Hardie and Garrett, 1977). The extensive areas of crinoidal-bryozoan-brachiopod wackestone and grainstone in the Leadville Limestone have no known modern analog. These carbonate rocks are believed to be of shallow-marine origin, having formed in less than 70 ft (21 m) of water, and to have been primarily bioclastic sands in which the fauna lived on areas of hard ground (Ramsbottom, 1978).

Crinoidal-bryozoan-brachiopod wackestone and packstone are abundant in the Leadville Limestone and are very common in Mississippian carbonate rocks throughout North America (Mamet, 1976; Armstrong and Mamet, 1977a). In the subsurface, Osagean carbonate rocks equivalent to part of the Leadville Limestone have a persistent 100- to 250-ft-thick (31–76 m) zone of replacement or secondary dolomite (pl. 1, sec. *A–A'*). The replacement dolomite has a relic texture of crinoids, foraminifera, and brachiopods that indicates the rock was a crinoid packstone or wackestone. Fine-grained dolomite containing anhydrite crystals or pseudomorphs of anhydrite and gypsum is interbedded within the replacement dolomite (Armstrong and Mamet, 1976, pl. 2). In the San Juan basin, most of the Mississippian oil and gas is in this replacement dolomite. The Lisbon oil field of southeastern Utah, northwest of the basin, has estimated reserves of 43 million barrels of oil in the dolomite. The relationship between the oil and gas and the dolomite is shown in cross section *A–A'* (pl. 1), and Mississippian oil and gas fields are summarized in appendix 2.

DEPOSITIONAL AND TECTONIC HISTORY

The Jemez lineament was defined by Mayo (1958) as one of several large northeast-trending lineaments that transect the southwestern United States (fig. 6). Its Pliocene to Quaternary expression is a series of volcanic

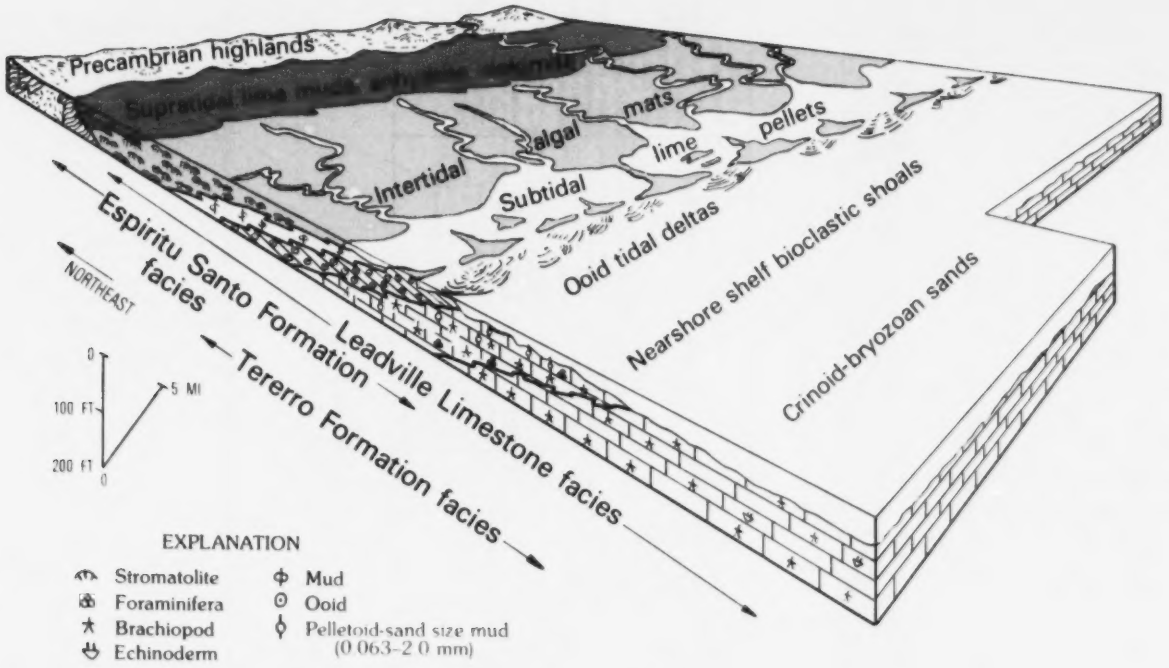
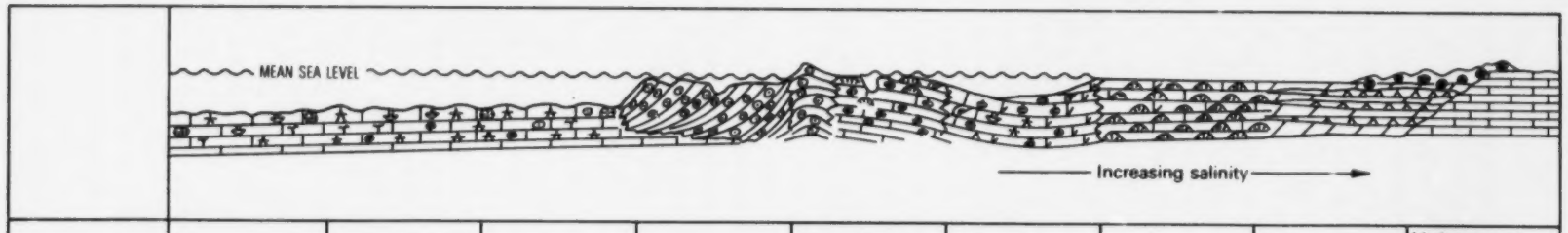


Figure 4. Carbonate facies relationships of the Mississippian Leadville Limestone and Espiritu Santo Formation of the Arroyo Penasco Group. Environments of deposition were shallow marine to supratidal, under conditions similar to those in the modern Persian Gulf.

fields from Raton, N. Mex., to the San Carlos–Peridot volcanic field of Arizona. Aldrich and others (1986) believed the geological and geophysical data suggest that the lineament is a structural zone extending deep into the lithosphere and that its location was controlled by ancient zones of weakness in the Precambrian basement. Geochronological investigations of Precambrian rocks in the southwestern United States suggest that the Jemez lineament may reflect the location of a suture in the Precambrian basement. L.T. Silver (unpublished data *in* Cordell, 1978) drew a boundary between Precambrian provinces that is essentially coincident with the lineament. The lineament approximately follows Silver's boundary between 1.65–1.73 billion-year-old supracrustal rocks to the north and 1.40–1.50 billion-year-old quartzite granite terrane to the south. The Jemez lineament, as shown in figure 6, marks the approximate southern flank of the San Juan basin. Chapin and Cather (1981) suggested that a best fit for the lineament is through the Tijeras-Canoncito fault system that intersects the Rio Grande rift. They further suggested that the Jemez and Tijeras lineaments are the same Precambrian zone of weakness that was offset 56–75 mi (90–120 km) by Precambrian, late Paleozoic, and Laramide strike-slip movement (fig. 6). The Jemez lineament does not appear to have influenced the distribution of facies patterns of Mississippian rocks.

Kelley and Clinton (1960, fig. 9) illustrated and described a series of northwest-oriented lineaments and the northeast-oriented Hogback trend in the Four Corners region (fig. 6). Their structural ideas were further developed by Baars (1966, 1976), Gorham (1975), Stevenson (1983a, b), and Stevenson and Baars (1977), all of whom argued that a large northwest-trending graben consisting of upper Precambrian through Mississippian rocks is exposed in the core of the San Juan Mountains. The latter workers believed tectonism was rejuvenated periodically throughout the Paleozoic and that movement on these structural lineaments actively controlled sedimentation through Mississippian time. Baars (1966, 1976) and Stevenson and Baars (1977) extended the structural relationships observed in the San Juan Mountains into the subsurface of the San Juan basin, where they showed these lineaments to be aligned at almost right angles to the Jemez lineament (fig. 6). The northwest-trending pattern or configuration of Mississippian rocks in the San Juan basin is parallel with the Paleozoic fault system of Kelley and Clinton (1960) and Baars (1966, 1976) (fig. 6).

A simplified Late Devonian paleogeographic and paleotectonic map for the area of the San Juan basin is shown in figure 7. Unpublished subsurface studies of Devonian rocks made by Armstrong in 1965–1966 suggest that the Defiance highlands stood as Precam-



FACIES	Tidal shelf	Crinoid-bioclastic sands	Nearshore shelf	Tidal delta and tidal channel	Frontal beaches and oolitic dunes; back-beach algal mats and lime mudstone	Restricted platform, subtidal lagoon, and channel zone	Intertidal	Supratidal	Vadose weathering of sabkha surface; carbonate dune sands, calcrete, and caliche
LITHOLOGY	Interbedded, thin- to medium-bedded lime mudstone, dolomite, and chert	Crinoid-bryozoan-brachiopod packstone-wackestone; lenticular to nodular chert	Bioclastic wackestone-packstone to pelletoid lime mudstone; abundant foraminifera	Bipclastic-oolitic packstone and grainstone	Inclined oolitic packstone and grainstone; lime mudstone with algal mats; tidalite deposits backside	Pelletoid lime mudstone, crinoid wackestone, packstone, dolomite; brachiopods, ostracodes	Algal mat, stromatolites with skeletal pelletal carbonate sand and mud; dolomite and gypsum	Seams and nodules of anhydrite, micrite, and dolomite; displaced microfauna, fine quartz sand	Coated particles, peloids, and pisolites; alternating microlaminae; limpid dolomite
COLOR	Gray to brown	Gray to light gray	Gray to light gray	Light gray	Gray to light gray	Light gray to gray	Gray yellow to brownish red	Gray, yellow, orange, brownish red	Gray, light gray, yellowish red
BEDDING AND SEDIMENTARY STRUCTURES	Thoroughly bedded; thin to medium wavy to nodular bedded. Surfaces show diastems of dark-gray to black chert	Crossbedded, massive beds common. Nodular gray chert	Stratified; abundant ripple marks; bioturbated. Nodular gray chert	Cross-stratified; abundant ripple marks	Steeply inclined; cross-stratified. Scattered carbonate lithoclasts	Bioturbation; tidal channel lags and fill of coarse material	Stromatolites; pseudomorphs after gypsum; tidal channel lag and fill of coarse material; birds eye structures, lime mud chips	Anhydrite and gypsum rhombs; bedded anhydrite; lime mud chips; algal mats; tepee structures	Large chips and chunks of carbonates; thick zone of caliche

EXPLANATION

Solitary coral · Brachiopod · Foraminifera · Ooid, coated
Echinoderm · Stromatolite · Mud, silt-sized · Pisoid, coated
Bryozoan · Ostracode · Crossbedding

Figure 5. Carbonate rock types and environments of deposition for the Mississippian Leadville Limestone and Arroyo Penasco Group, San Juan basin and adjacent areas.

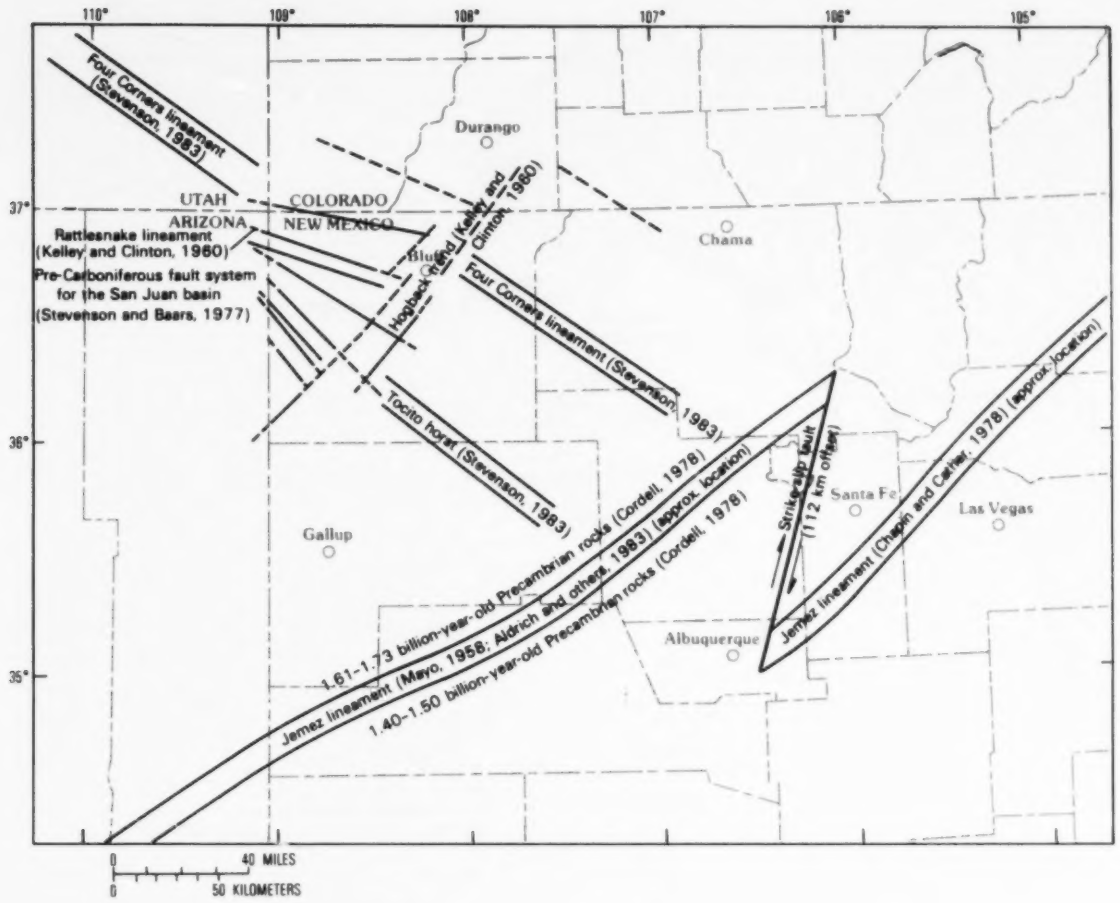


Figure 6. Precambrian and early Paleozoic structural features, San Juan basin and adjacent areas.

brian monadnocks that shed detrital quartz into adjacent marine environments. Preserved Devonian rocks are restricted to the western part of the San Juan basin, between the Uncompahgre and Zuni-Defiance highlands. A small outlier of Upper Devonian Elbert Formation is preserved in the center of the basin. The hiatus between the Devonian and the Mississippian Systems represents latest Famennian and much, if not all, of Kinderhookian time. Extensive erosion of Devonian sediments must have occurred during this time, and the contact between the two systems is a paraconformity.

Marine transgressions and regressions in the Late Devonian and Mississippian of New Mexico are probably related to events of the Antler orogeny to the northwest in Nevada. Orogenic pulses are reflected in the Upper Devonian sediments and in the regional hiatus between Upper Devonian and Mississippian rocks in Nevada, Arizona, and New Mexico (Poole and Sandberg, 1977; Schumacher, 1978).

Mississippian strata disconformably overlie the Upper Devonian (Famennian) Ouray Limestone in the western part of the San Juan basin and the older Upper Devonian Elbert Formation and Precambrian igneous and metamorphic rocks in the central part of the basin. Wherever the Devonian rocks are carbonates, the basal Mississippian rocks generally are limestone, and wherever Mississippian rocks rest on Precambrian rocks, the basal Mississippian rocks commonly comprise a 0.5- to 3-ft-thick (0.15–1 m) bed of white quartz conglomerate and sandstone.

Basal beds of the Mississippian are diachronous. The marine transgression came from the northwest and west between the Uncompahgre and Zuni-Defiance highlands. The oldest Mississippian beds are in the subsurface of southeastern Utah and in northwestern New Mexico and are carbonate rocks of possible Kinderhookian(?) to early Osagean (pre-zone 7?, zone 7) age. By late Osagean time (zone 9), a regional inundation had

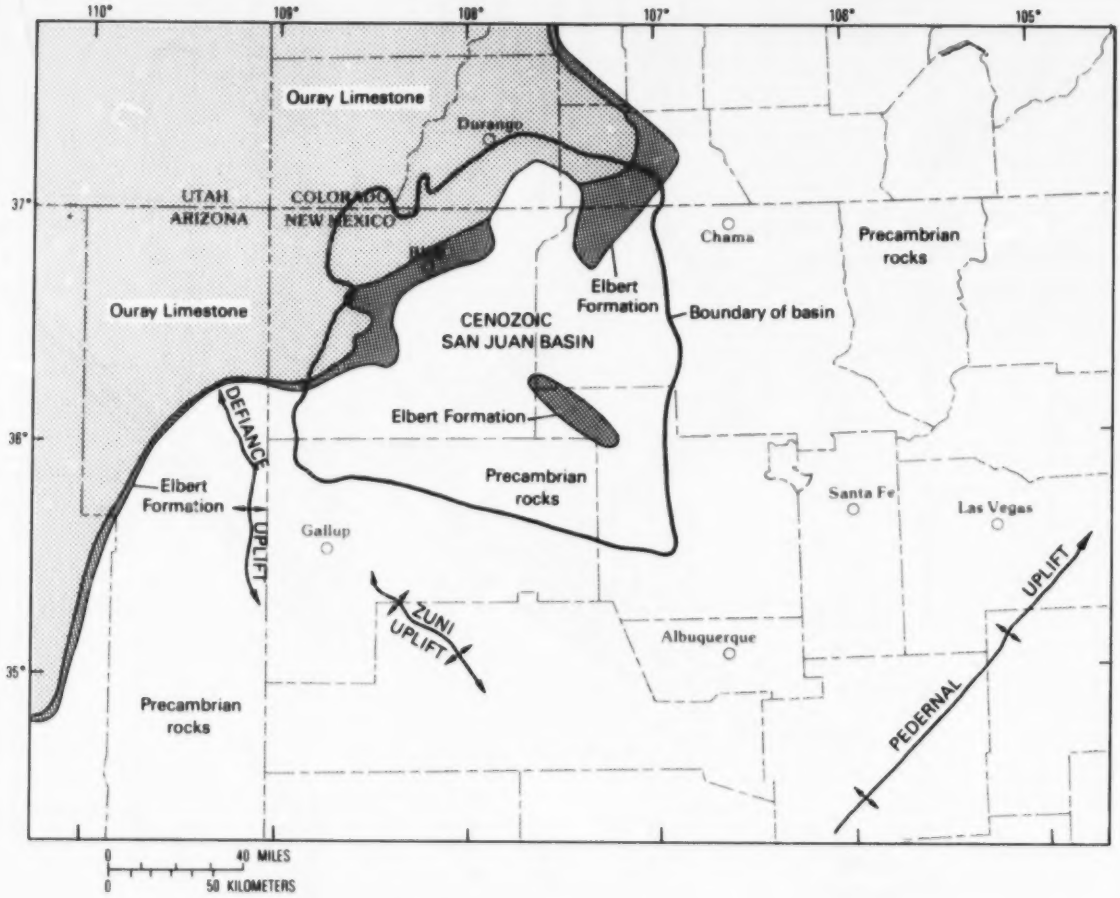


Figure 7. Late Devonian paleogeography and paleotectonics, San Juan basin and adjacent areas.

occurred that extended from southern New Mexico and Arizona and northeast Arizona and southeast Utah into northern and central New Mexico. Figure 8 shows a theoretical reconstruction of depositional environments for the Leadville Limestone of the San Juan basin and the Arroyo Penasco Group of north-central New Mexico. In the area of the San Juan basin, Osagean and Meramecian carbonate rocks typically are bioclastic sandstones composed of crinoids, brachiopods, bryozoans, pellets, ooids and oolites, lime mudstone, and dolomite. They were deposited in shallow-water to supratidal-sabkha environments. A schematic reconstruction of Mississippian carbonate facies relationships and Precambrian highlands in northern New Mexico and adjacent parts of Colorado, Utah, and Arizona is shown on figure 8.

The end of Osagean time was marked by a regional hiatus that has been recognized over a large area (Gutschick and others, 1980). B.L. Mamet (written commun., 1987) believed that the Osagean-Meramecian (Tournaisian-Visean) boundary is worldwide and profound in North America and the Russian platform. Detailed studies of outcrop sections in the San Pedro and Nacimiento Mountains on the east side of the San Juan basin show that the hiatus is zone 10–13 (fig. 3) and that the overlying Meramecian carbonates are pelloid-ooid-crinoid-foraminifera wackestone to packstone (Armstrong and Mamet, 1974, 1976). Meramecian carbonate rocks can be traced in the subsurface into the Blanding basin of southeastern Utah (pl. 1, sec. *A–A'*).

The isopach maps of Mississippian strata shown in figures 9 and 10 are based on the pre-Pennsylvanian erosional remnants of Mississippian rocks. During Late Mississippian (Chesterian) and Early Pennsylvanian (Morrowan) time, Mississippian strata were elevated, eroded and dissected, and during Pennsylvanian and Permian time, large areas of Mississippian strata were eroded from structurally active features such as the Zuni, Defiance, Uncompahgre, and Pedernal uplifts.

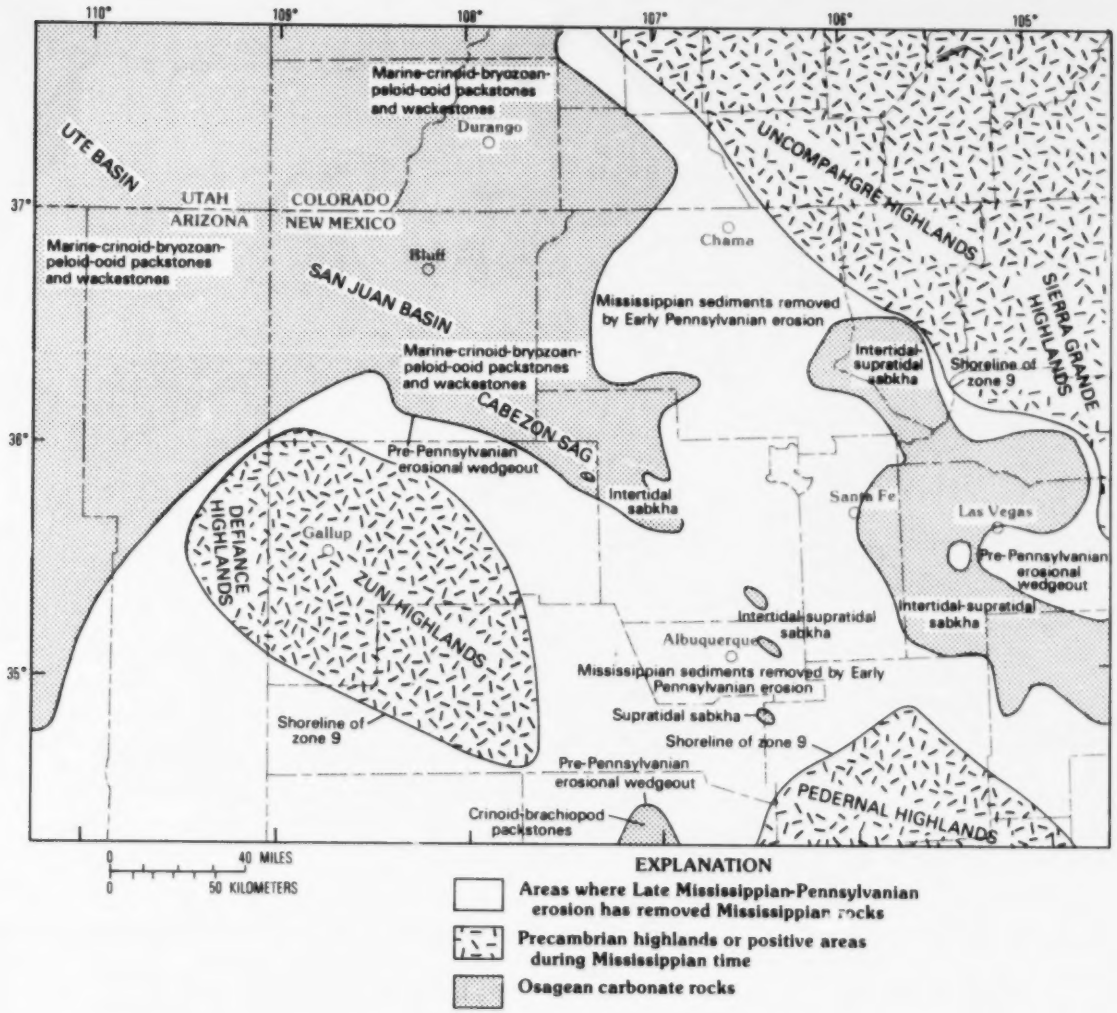


Figure 8. Depositional environments at the end of zone-9 Osagean time for the Leadville Limestone of the San Juan basin area of New Mexico and Colorado, the Redwall Limestone of Arizona and Utah, and the Arroyo Penasco Group of north-central New Mexico.

The Chesterian Log Springs Formation in the Nacimiento and San Pedro Mountains on the east flank of the San Juan basin is a continental-fluvial clastic red-bed sequence that unconformably overlies Mississippian carbonate rocks. Sediments comprising the Log Springs Formation vary from mud and silt to boulder and were derived from erosion of Precambrian igneous and metamorphic and Mississippian carbonate terranes. Stratigraphic and paleontologic evidence indicates that the tectonic movement that heralded the Pennsylvanian began in the eastern part of the San Juan basin by Chesterian time. The Molas Formation in the subsurface of the San Juan basin and in outcrops in the San Juan Mountains is a paleosol that developed on the Leadville Limestone and was reworked by the Pennsylvanian marine transgression. Its age may range from late Chesterian to Early Pennsylvanian.

During Late Mississippian and Early Pennsylvanian time, strong tectonic events occurred that probably are related to the Carboniferous-age Ouachita orogeny, an arc-continent or continent-continent collision (Kluth and Coney, 1981; Dickinson, 1982). Major structural elements rejuvenated by this event include the Uncompahgre uplift, a northwest-trending fault block that forms the northern boundary of the San Juan basin, the Penasco uplift at the eastern boundary of the San Juan basin, and the ancestral Zuni uplift that consists of the Zuni uplift, an east-west structural alignment,

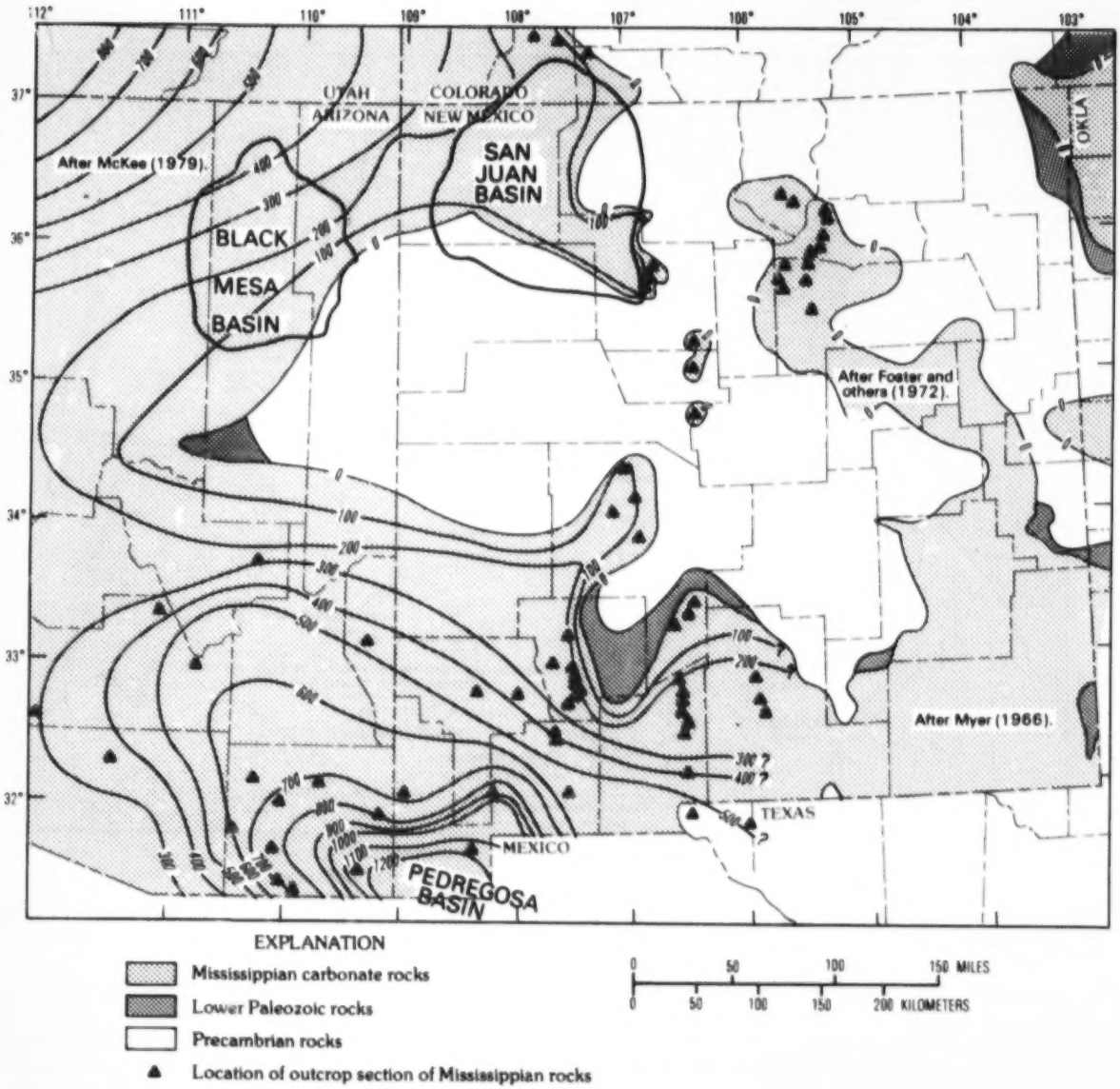


Figure 9. Isopach map for Mississippian rocks in New Mexico and eastern Arizona (interval 100 ft). Patterns of thickness and distribution are influenced, in part, by Late Mississippian and Early Pennsylvanian tectonism and erosion.

and the Defiance salient or uplift, a north-plunging structural nose on the northern flank of the Zuni uplift (Szabo and Wengerd, 1975).

SUMMARY

During Mississippian time, the area of the San Juan basin was part of a northwest-trending, broad, shallow sag between the San Juan highlands (Uncompahgre uplift) to the north and the Zuni-Defiance uplift to the south. By latest Kinderhookian or early Osagean time, marine waters from the northwest had flooded the area of the San Juan basin, and near the end of Osagean time marine waters covered much of northern New Mexico. At the end of Osagean time, regional uplift and erosion of the Lower Mississippian carbonate rocks had occurred, and a thin sequence of Meramecian carbonate rocks was deposited on the Osagean erosion surface. Mississippian strata of the San Juan basin region include dolomite, lime mudstone, bioclastic limestone, and encrinite. During Late Mississippian and Early Pennsylvanian time, Mississippian carbonate strata were subjected to extensive erosion and karsting.

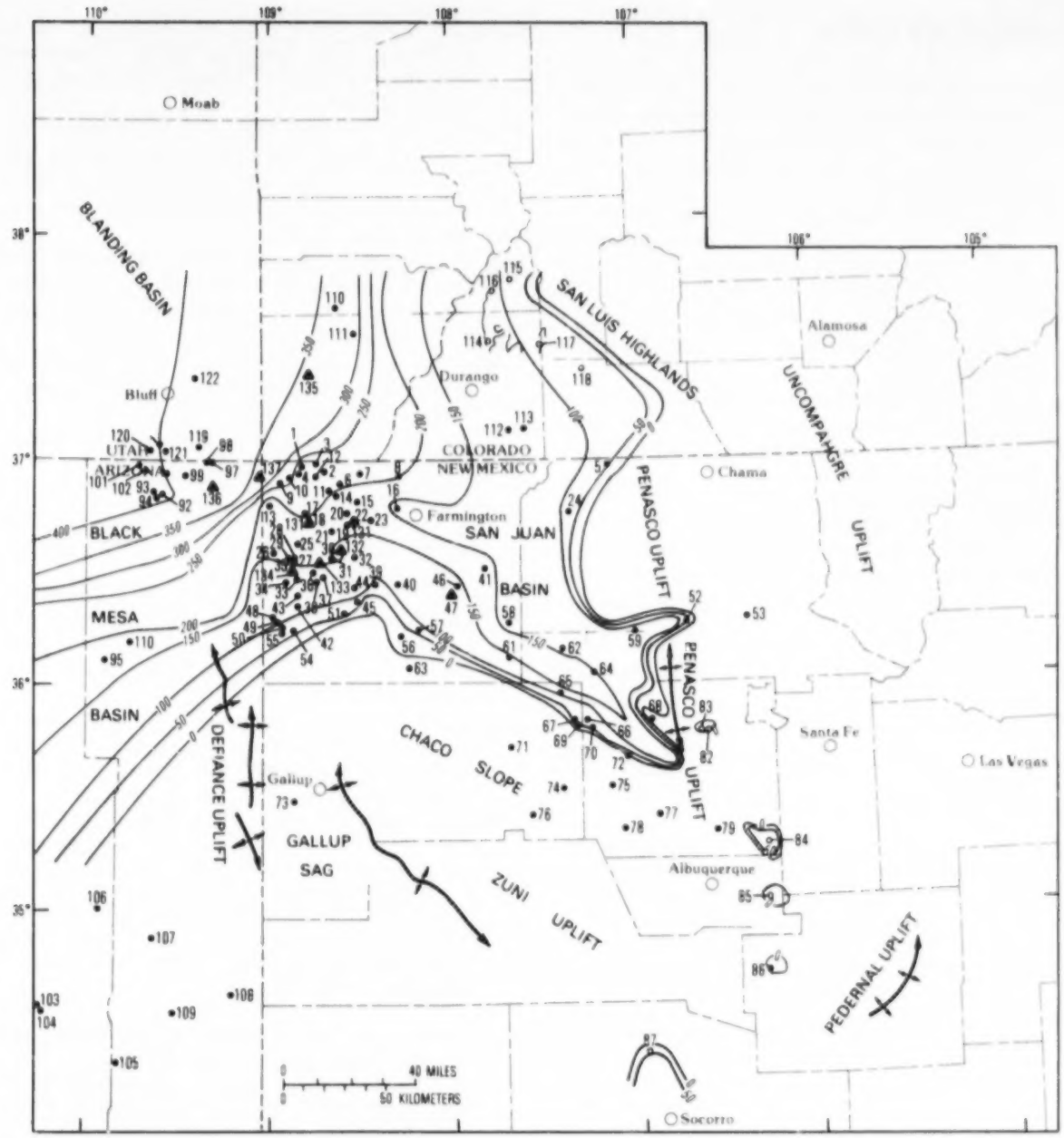


Figure 10. Isopach map for Mississippian rocks in the San Juan basin and adjacent areas at the end of the Carboniferous (interval 50 ft). Regional late Paleozoic structural features are shown; the names of the structural features are, in part, after Kelley and Clinton (1960) and Wengerd (1962). Solid circles indicate well locations; open circles indicate outcrop locations; all listed by number in appendix 1. Triangles indicate locations of small oil or gas field; listed by number in appendix 2.

Shows and noncommercial oil and gas pools are known from the Leadville Limestone in the San Juan basin of New Mexico. The principal reservoir beds are fractured limestone and vuggy dolomite in the western and deeper part of the basin. Most likely, any future oil and gas found in the Mississippian of the San Juan basin will be associated with basement structures, although the trap probably will be stratigraphic (Stevenson, 1983b).

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APPENDIXES 1 AND 2

Appendix I. Locations of exploration wells and Mississippian surface outcrops used in study

[Well and outcrop locations are shown by number on figures 1 and 10 and on plate 1]

No.	Well or location name	Sec.	T.	R.
	New Mexico subsurface data			
1.	Continental Oil Company No. 21-1 Navajo	21	32 N.	19 W.
2.	Texaco Incorporated No. 1 Navajo-AJ	35	32 N.	18 W.
3.	Texas Company No. 1 Navajo "N"	17	32 N.	18 W.
4.	Compass Exploration Incorporated No. 1-33 Indian	33	32 N.	19 W.
5.	Pan American Petroleum No. 1 Pagosa Jicarilla	23	32 N.	3 W.
6.	Reynolds Mining Corporation No. 1 Navajo Lease 7652	22	31 N.	17 W.
7.	Standard Oil of Texas No. 6-1 Navajo Ute	3	31 N.	16 W.
8.	Pan American No. 1 Ute Mountain Tribal "D"	10	31 N.	14 W.
9.	British American Oil Production No. 1 Navajo "E"	15	31 N.	20 W.
10.	Monsanto No. 1 Natoni	7	31 N.	19 W.
11.	Standard Oil of Texas No. 2 Navajo 21-36	36	31 N.	18 W.
12.	Humble Oil and Refining No. 1 Navajo "H"	4	31 N.	18 W.
13.	Pan American Petroleum No. 1 Navajo Tribal-AD	13	30 N.	21 W.
14.	Phillips Petroleum No. 1 Navajo	5	30 N.	17 W.
15.	Pan American Petroleum No. 1-A O.J. Hoover	23	30 N.	16 W.
16.	Mountain Fuel Supply Company No. 1 Fruitland	28	30 N	14 W.
17.	Continental No. 100 Rattlesnake	2	29 N.	19 W.
18.	U.S. Bureau of Mines No. 1-G Rattlesnake	13	29 N.	19 W.
19.	M.M. Garrett No. 1 Navajo	25	29 N.	17 W.
20.	Pan American Petroleum No. 1 Navajo	1	29 N.	17 W.
21.	Amerada Petroleum No. 1 Navajo Tract-20	31	29 N.	17 W.
22.	Stanolind Oil & Gas Company No. 13 USG	19	29 N.	16 W.
23.	Humble Oil & Refining Company No. 1 Navajo	18	29 N.	15 W.
24.	El Paso Natural Gas Company No. 50	7	29 N.	5 W.
25.	Amerada Petroleum No. 1 Navajo-32	27	28 N.	19 W.
26.	Texaco Incorporated No. 1 Navajo Tribe-AW	7	27 N.	20 W.
27.	Texaco Incorporated No. 1 Navajo AS	28	27 N.	19 W.
28.	Northwest Pipeline Corporation No. 2 Barbara Kay	21	27 N.	19 W.
29.	Northwest Pipeline Corporation No. 1 Barbara Kay	20	27 N.	19 W.
30.	Continental Oil Company No. 24 Table Mesa	4	27 N.	17 W.
31.	Amerada Petroleum Corporation No. 1 Navajo-Tract 4	20	27 N.	17 W.
32.	Continental Oil Company No. 1 Chaco Wash-Navajo	19	27 N.	16 W.
33.	Apache Corporation No. 1-21 Navajo Tribal Tract 52	21	26 N.	19 W.
34.	Gulf Oil Company No. 1 Navajo "BB"	25	26 N.	20 W.
35.	Amerada Petroleum Corporation No. 1 Navajo-Tract 381	5	26 N.	19 W.
36.	Pan American Petroleum No. 1 Navajo-P	8	26 N.	18 W.
37.	Sinclair Oil & Gas Company No. 1 Navajo-149	23	26 N.	18 W.
38.	Texaco Incorporated No. 1 Navajo AL	28	26 N.	18 W.
39.	Pure Oil Company No. 1 Navajo Tract 27	32	26 N.	15 W.
40.	Skelly Oil Company No. 1 Navajo-O	34	26 N.	14 W.
41.	El Paso Natural Gas Company No. 265 Huerfano	12	26 N.	10 W.
42.	Texaco Incorporated No. 1 Navajo-AO	33	25 N.	19 W.
43.	Champline Petroleum Company No. 1 Navajo-Humble	16	25 N.	19 W.
44.	Pan American No. 1 Gulf-Navajo	4	25 N.	16 W.
45.	Gulf Oil Company No. 1 Navajo Federal	28	25 N.	16 W.
46.	Tenneco Oil Company No. 1 Pah	3	25 N.	11 W.
47.	Shell Oil Company No. 113-17 Carson Unit	17	25 N.	11 W.
48.	Kerr McGee Corporation No. 1 Navajo K	20	24 N.	20 W.
49.	Kerr McGee Corporation No. 1 Navajo L	28	24 N.	20 W.
50.	Kerr McGee Corporation No. 1 Navajo I	34	24 N.	20 W.

Appendix 1. Continued

No.	Well or location name	Sec.	T.	R.
51.	Amoco Production Company No. 1 Navajo Tribal "AA"	14	24 N.	17 W.
52.	Skelly Oil Company No. 1 Crittenden	36	24 N.	1 E.
53.	James T. Watson No. 1 Arthur N. Pack	35	24 N.	4 E.
54.	Kerr McGee Corporation No. 1-A Navajo	12	23 N.	20 W.
55.	Kerr McGee Corporation No. 1 Navajo-M	9	23 N.	20 W.
56.	Woods Petroleum Corporation No. 1-22 Navajo	22	23 N.	14 W.
57.	Apache Corporation No. 1 Foshay	9	23 N.	13 W.
58.	Sun Oil Company No. 1 Ah Des Pi All-Navajo	12	23 N.	9 W.
59.	Magnolia Petroleum Corporation No. 1-A Jicarilla	18	23 N.	2 W.
60.	H.A. Chapman No. 1-10 Navajo	10	22 N.	14 W.
61.	Sun Oil Company No. 1 Navajo Lands	25	22 N.	9 W.
62.	Sun Oil Company No. 1 El Paso Federal	10	22 N.	6 W.
63.	Southern Union No. 1 Navajo	1	21 N.	14 W.
64.	Union Oil Company of California No. 1-M-13 USA	13	21 N.	5 W.
65.	Sun Oil Company No. 1 New Mexico State "W"	16	20 N.	6 W.
66.	Dome Petroleum Corporation No. 1 Federal 26 Tinian	26	19 N.	5 W.
67.	James P. Dunican, Incorporated No. 1 Santa Fe	31	19 N.	5 W.
68.	El Paso Natural Gas Company No. 1 Elliott State	36	19 W.	2 W.
69.	M.F. Abraham No. 1 Star Lake Unit	5	18 N.	5 W.
70.	Gulf Oil Company No. 1 Torreon	12	18 N.	5 W.
71.	Great Western Drilling Company No. 1 Hospah	1	17 N.	9 W.
72.	Brinkerhoff Drilling Company No. 1 Cabezon-Gov't	7	17 N.	3 W.
73.	Kerr McGee Corporation No. 1 Santa Fe	19	15 N.	19 W.
74.	Richfield Oil Corporation No. 1 Drought-Booth	4	15 N.	6 W.
75.	Houston Oil and Mineral No. 2 Booth Drought	1	15 N.	4 W.
76.	Superior Oil Company San Mateo Gov't 1-14	14	14 N.	8 W.
77.	Humble Oil & Refining Company No. 1-B Sante Fe	20	14 N.	1 W.
78.	Texaco Incorporated No. 1 Howard Major	10	13 N.	3 W.
79.	Shell Oil Company No. 1 Santa Fe	18	13 N.	3 E.
	New Mexico surface outcrops			
80.	San Pedro Mountains	36	23 N.	1 W.
81.	Pinos Canyon, Nacimiento Mountains	5	16 N.	1 E.
82.	Soda Dam, Jemez Mountains	14	18 N.	2 E.
83.	Guadalupe Box, Jemez Mountains	17	17 N.	2 E.
84.	Placitas, Northern Sandia Mountains	34	13 N.	5 E.
85.	Tijeras Canyon, Manzanita Mountains	21	10 N.	5 E.
86.	Bosque Peak, Manzanos Mountains	4	6 N.	5 E.
87.	Ladron Mountains	30	2 N.	2 W.
88.	Jack's Creek, Sangre de Cristo Mountains	34	19 N.	12 E.
89.	Tererro, Sangre de Cristo Mountains	33	18 N.	12 E.
90.	Dalton Picnic Grounds, Sangre de Cristo Mountains	32	17 N.	12 E.
91.	Magdalena Mountains	31	2 S.	3 W.
	Arizona subsurface data			
92.	Texas Pacific Coal & Gas Company Navajo Tract 190	20	40 N.	26 E.
93.	Pan American Petroleum Corporation Toh-la-con	11	40 N.	25 E.
94.	Bonanza Oil Corporation Navajo No. 1	30	40 N.	26 E.
95.	Vaughey & Vaughey & Blackburn Navajo No. 6-1	6	36 N.	28 E.
96.	Navajo-Black Mountain No. 1	26	32 N.	23 E.
97.	Shell Oil Company No. 2 Boundary Butte	3	41 N.	28 E.
98.	Humble No. 1 Navajo Tribal	4	41 N.	28 E.
99.	Hancock No. 1 Dinne-Federal	29	41 N.	27 E.
100.	Gulf Oil Company No. 1 Walker Creek-Navajo	28	41 N.	26 E.
101.	Midwest No. 1 Navajo	7	41 N.	23 E.

Appendix 1. Continued

No.	Well or location name	Sec.	T.	R.
102.	Texaco Incorporated Navajo Tribe "AC" No. 1	16	41 N.	25 E.
103.	Union-Continental No. 1 New Mexico-Arizona Land	34	15 N.	19 E.
104.	Lockhart No. 1 Aztec Land & Cattle Company	33	14 N.	20 E.
105.	Pan American Petroleum B-1 New Mexico-Arizona Land	25	12 N.	23 E.
106.	General Petroleum 14-6 Creager-State	6	19 N.	23 E.
107.	Kerr McGee No. 1 Hortenstein	23	18 N.	25 E.
108.	Argo No. 2 State	22	15 N.	29 E.
109.	Franco-Arizona No. 1 Government	14	14 N.	26 E.
	Colorado subsurface data			
110.	Parker and McCune Ferris Trails No. 1	16	39 N.	16 W.
111.	California Company Lebanon Unit No. 1	20	38 N.	15 W.
112.	Amoco Production Company No. 1 Jessie Hahn	15	33 N.	8 W.
113.	Stanolind Oil & Gas No. 6 Ute Indian B	17	33 N.	7 W.
	Colorado surface outcrops			
114.	Rockwood Quarry 65A-12	12	37 N.	9 W.
115.	Molas Lake 66C-2B & 2A	7	40 N.	7 W.
116.	Coalbank Hill 66C-1	6	39 N.	8 W.
117.	Vallecito 66C-3	16	37 N.	6 W.
118.	Piedra River 65A-10	22	36 N.	4 W.
	Utah subsurface data			
119.	Ohio Oil Company Navajo Tract 74-1	16	43 S.	23 E.
120.	Texaco Incorporated Navajo AE No. 1	19	43 S.	21 E.
121.	Davis Oil Company Chinle Wash No. 1	23	43 S.	21 E.
122.	Shell Oil Company Bluff No. 1	32	39 S.	23 E.
123.	Ohio Oil Company Navajo No. 1	10	43 S.	21 E.
124.	Skelly Oil Company Summit Point No. 1	21	31 S.	25 E.
125.	Pure Oil Company Northwest Lisbon U.S.A. D-1	14	30 S.	24 E.
126.	Pure Oil Company Horsehead Unit No. 1	18	29 S.	21 E.
127.	Shell Oil Company Murphy Range Unit No. 1	18	28 S.	19 E.
128.	Pan American Petroleum Company Salt Wash No. 1	15	23 S.	17 E.
129.	Mobil Oil Company Jakey's Ridge No. 12-3	3	23 S.	16 E.

Appendix 2. Oil and gas occurrences in Mississippian rocks of the San Juan basin and adjacent areas

[Location number precedes field name; location is shown on plate 1 by number. From Fassett and Thomaidis (1978) and Thomaidis (1983)]

130. Rattlesnake (sec. 13, T. 29 N., R. 19 W.), New Mexico — Commodity: helium
Producing formation: Leadville Limestone
Discovery well completed April 19, 1943; initial production 33,000 million cubic feet of gas per day (MCFGD). When the helium content of the discovery well was realized, the well was turned over to the U.S. Government as a helium reserve. A second well was completed on August 6, 1943 for 17,300 MCFGD with no treatment. Both wells were plugged in November 1968.

131. Hogback (sec. 19, T. 29 N., R. 16 W.), New Mexico — Commodities: oil, gas
Producing formation: Leadville Limestone
Discovery well completed October 15, 1952; initial potential 146.93 barrels of oil (BO), 6 barrels of water (BW), and 14,900 MCFG per day. No producing wells, two abandoned wells.

132. Table Mesa (sec. 9, T. 27 N., R. 17 W.), New Mexico — Commodities: oil, gas
Producing formation: Leadville Limestone
Continental Oil No. 17 well completed January 1951; 21,185 barrels of oil produced by the end of November 1951. Within a year, daily production declined from 100 to 17 barrels. All wells were plugged and abandoned in 1975. Actual recovery: 1,193,006 MCFG, 74,393 BO. Helium content of gas produced was 5-6 percent.

133. Tocito Dome (sec. 34, T. 27 N., R. 18 W.), New Mexico — Commodity: helium
Producing formation : Leadville Limestone
Discovery well drilled in 1963 and found 1,006 MCFG. A second well was drilled in 1973, with 3,350 MCFGD. The gas comprises 7 percent helium and 90 percent nitrogen and has a Btu content of about 30. Cumulative production 1,104,668 MCFG. The two wells are now shut-in.

134. Beautiful Mountain (sec. 5, T. 26 N., R. 19 W.), New Mexico — Commodities: oil, helium
Producing formation: Leadville Limestone
Discovery well completed June 3, 1975, flowed 110 BO, 154 BW, and 38 MCFG per day, shut-in June 1976. The second well was completed early in 1978 as a Mississippian gas producer having initial potential of 325 MCFGD. Both wells yielded helium-bearing gas (7.14 percent helium) that was shipped by pipeline to a helium-extraction plant. Producing wells are now shut-in, and two dry holes were drilled.

135. McElmo Field (sec. 24, T. 36 N., R. 18 W.), Colorado — Commodity: carbon dioxide gas
Producing formation: Leadville Limestone
Discovery well completed July 17, 1947 and flowed 40,000 MCF of carbon dioxide gas per day. Production is from one well. Cumulative production to 1977, 3,541,709 MCFG.

136. Dry Mesa (sec. 11, T. 40 N., R. 28 E.), Arizona — Commodities: oil, gas
Producing formation: Leadville Limestone
Discovery well completed June 1959 and initially pumped 240 BO and 27 BW per day. Three producing wells and two dry holes were drilled. Cumulative production to January 1, 1984, 663,519 BO and 132,263 MCFG.

137. Undesignated (sec. 36, T. 41 N., 30 E.), Arizona — Commodity: helium
Producing formation: Leadville Limestone
Discovery well Texaco 1-Z was completed July 10, 1960.

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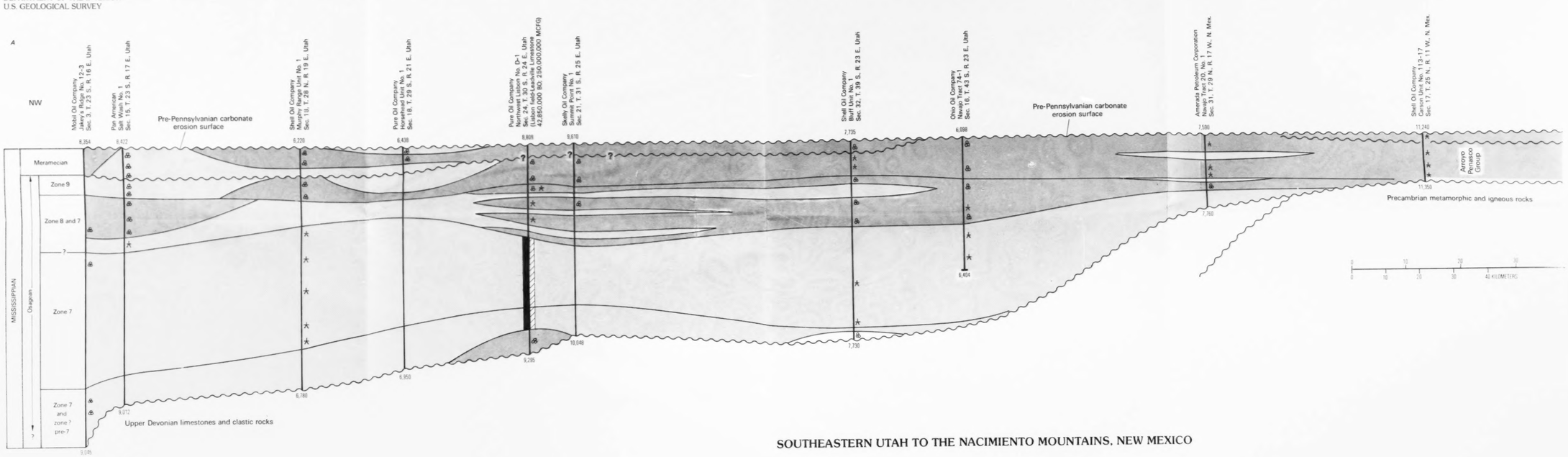
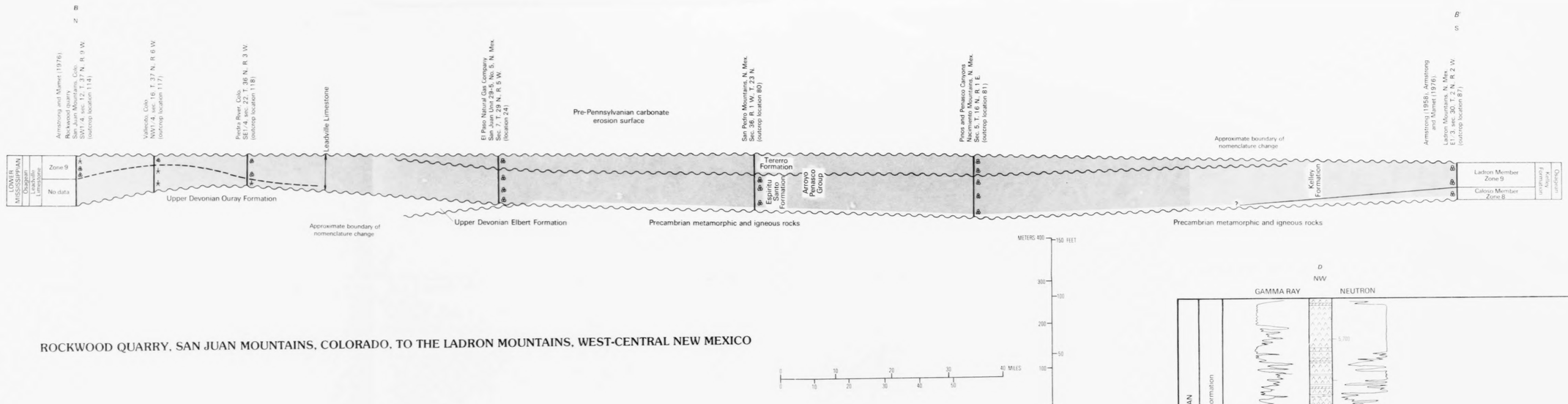
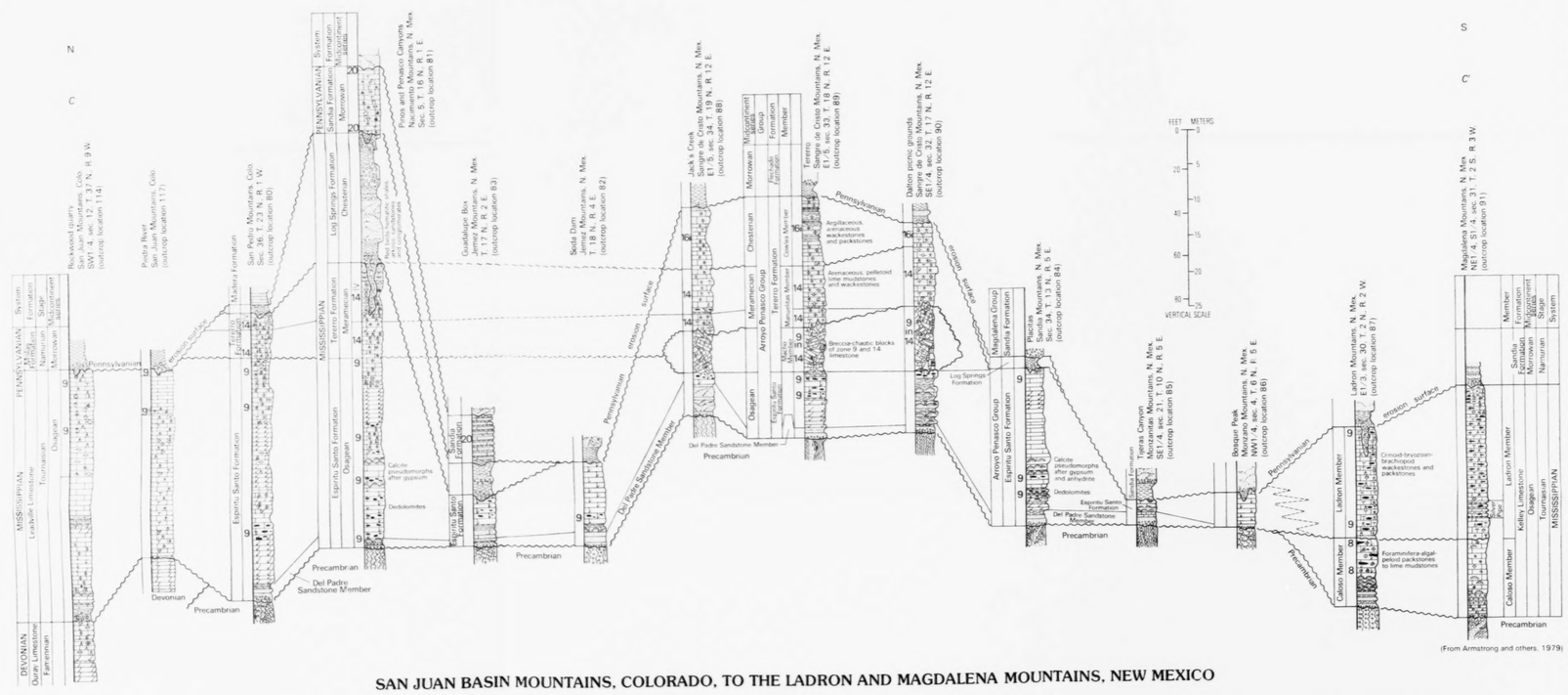


SOUTHEASTERN UTAH TO THE NACIMIENTO MOUNTAINS, NEW MEXICO



ROCKWOOD QUARRY, SAN JUAN MOUNTAINS, COLORADO, TO THE LADRON MOUNTAINS, WEST-CENTRAL NEW MEXICO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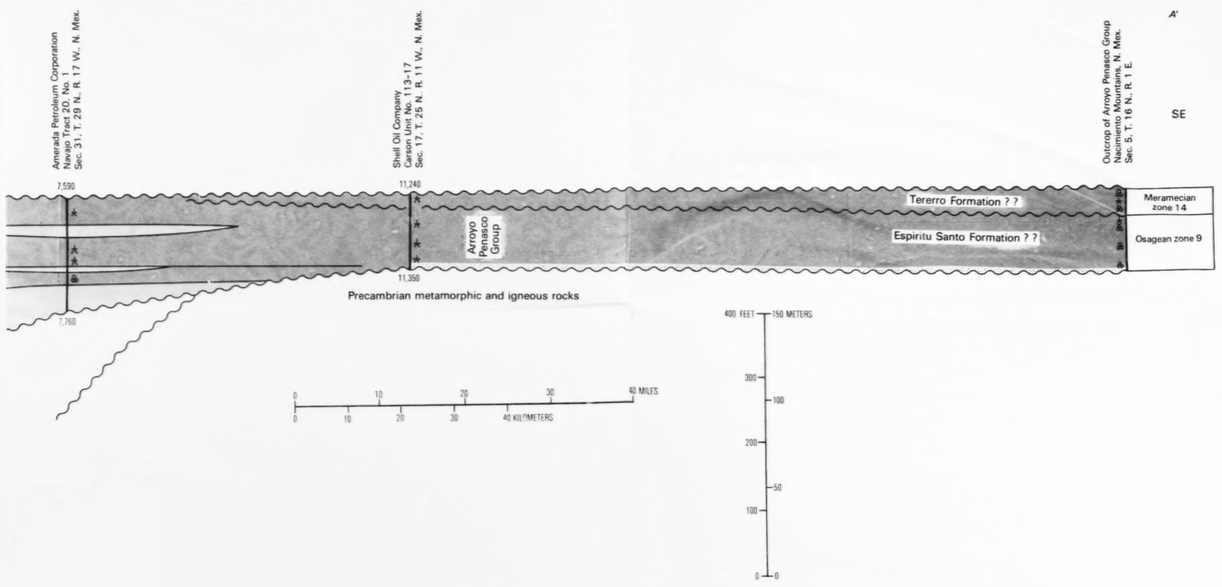
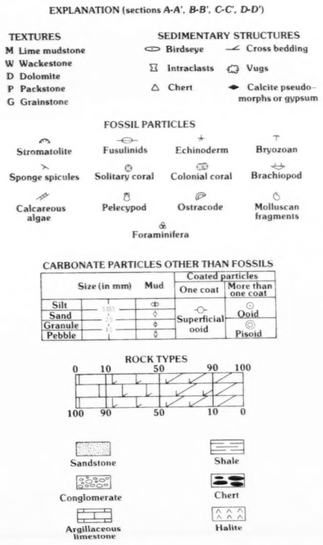
C
Rockwood quarry San Juan Mountains, Colo. SW1/4, sec. 12, T. 37 N., R. 9 W. (outcrop location 114)
Piedra River San Juan Mountains, Colo. (outcrop location 117)
San Pedro Mountains, Colo. Sec. 36, T. 24 N., R. 1 W. (outcrop location 80)
Pinos and Penasco Canyons, Nacimiento Mountains, N. Mex. Sec. 5, T. 16 N., R. 1 E. (outcrop location 81)
Guadalupe Box Jemez Mountains, N. Mex. T. 17 N., R. 2 E. (outcrop location 83)
Soda Dam Jemez Mountains, N. Mex. T. 18 N., R. 4 E. (outcrop location 82)
Jack's Creek Sangre de Cristo Mountains, N. Mex. E1/2, sec. 34, T. 19 N., R. 12 E. (outcrop location 88)
Tererro Sangre de Cristo Mountains, N. Mex. E1/5, sec. 33, T. 18 N., R. 12 E. (outcrop location 89)
Dalton picnic grounds Sangre de Cristo Mountains, N. Mex. SE1/4, sec. 33, T. 17 N., R. 12 E. (outcrop location 90)
Placitas Sandia Mountains, N. Mex. Sec. 34, T. 13 N., R. 5 E. (outcrop location 84)
Tijeras Canyon Monzanitas Mountains, N. Mex. E1/2, sec. 27, T. 10 N., R. 5 E. (outcrop location 85)
Bosque Peak Manzano Mountains, N. Mex. NW1/4, sec. 4, T. 6 N., R. 5 E. (outcrop location 86)
Ladron Mountains, N. Mex. E1/2, sec. 30, T. 2 N., R. 2 W. (outcrop location 87)
Magdalena Mountains, N. Mex. NE1/4, sec. 31, T. 2 S., R. 3 W. (outcrop location 91)
Pennsylvanian
Mississippian
Devonian
Precambrian
Del Padre Sandstone Member
Arroyo Penasco Group
Espiritu Santo Formation
Sandia Formation
Log Springs Formation
Magdalena Group
Argillaceous, arenaceous wackestones and packstones
Arenaceous, pelleted lime mudstones and wackestones
Breccia-chaotic blocks of zone 9 and 14 limestone
Calcite pseudomorphs after gypsum and anhydrite
Dedolomites
Crinoid-bryozoan-brachiopod wackestones and packstones
Foraminifera-algal-peloid packstones to lime mudstones
Erosion surface
Pennsylvanian
Precambrian
Precambrian
Precambr





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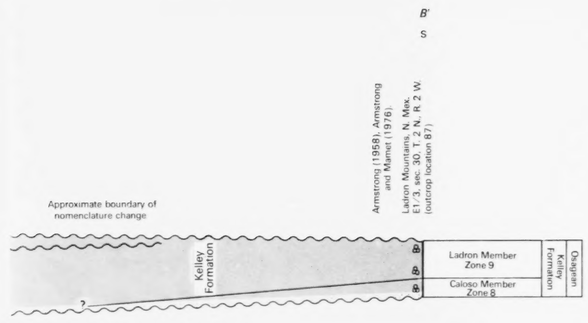

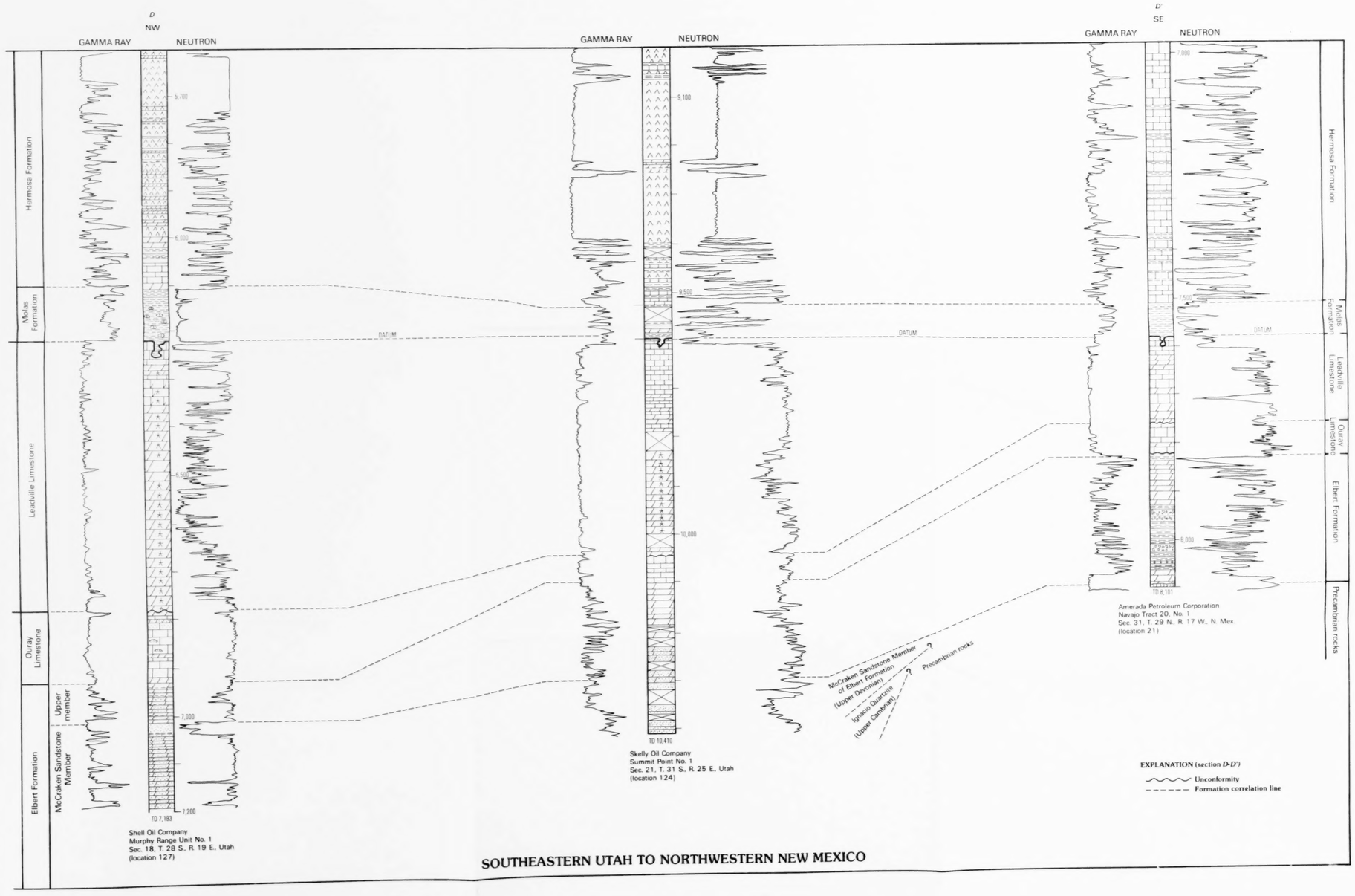

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